MARS FIELD GEOLOGY, BIOLOGY, AND PALEONTOLOGY WORKSHOP: SUMMARY AND RECOMMENDATIONS

November 18–19, 1998
Space Center Houston, Houston, Texas

LPI Contribution No. 968

MARS FIELD GEOLOGY, BIOLOGY, AND PALEONTOLOGY WORKSHOP: SUMMARY AND RECOMMENDATIONS

November 18–19, 1998
Space Center Houston

Edited by
Nancy Ann Budden
Lunar and Planetary Institute

Sponsored by
Lunar and Planetary Institute
National Aeronautics and Space Administration

Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113

LPI Contribution No. 968

Compiled in 1999 by
LUNAR AND PLANETARY INSTITUTE

The Institute is operated by the Universities Space Research Association under Contract No. NASW-4574 with the National Aeronautcis and Space Administration.

Material in this volume may be copied without restraint for library, abstract service, education, or personal research purposes; however, republication of any paper or portion thereof requires the written permission of the authors as well as the appropriate acknowledgment of this publication.

This volume may be cited as

Budden N. A., ed. (1999) *Mars Field Geology, Biology, and Paleontology Workshop: Summary and Recommendations.* LPI Contribution No. 968, Lunar and Planetary Institute, Houston. 80 pp.

This volume is distributed by

ORDER DEPARTMENT
Lunar and Planetary Institute
3600 Bay Area Boulevard
Houston TX 77058-1113
Phone: 281-486-2172
Fax: 281-486-2186
E-mail: order@lpi.jsc.nasa.gov

Mail order requestors will be invoiced for the cost of shipping and handling.

Cover: Mars test suit subject and field geologist Dean Eppler overlooking Meteor Crater, Arizona, in Mark III Mars EVA suit.

PREFACE

In November 1998 the Lunar and Planetary Institute, under the sponsorship of the NASA/HEDS (Human Exploration and Development of Space) Enterprise, held a workshop to explore the objectives, desired capabilities, and operational requirements for the first human exploration of Mars. The goal of the workshop was to formulate recommendations that would ultimately contribute to NASA policy regarding the human exploration of Mars. Participants included world-class field geologists and geochemists, biologists, paleontologists, Apollo astronauts who explored the Moon, the scientists who trained them, shuttle and future space station astronauts, the NASA/JSC EVA office, and NASA mission planners. Together this group examined the realties of planning and executing an exploration campaign on the surface of Mars that would result in observations and sampling that would help define the present composition, morphology, and geologic evolution of Mars, and shed light on whether life ever existed on the planet. Current NASA planning envisions sending a crew of six people to Mars, as early as 2013, to conduct a long-term expedition. The crew will spend a year and a half on Mars and will have considerable mobility, along with sampling and analytical capability, in an area of high scientific interest. The workshop used these parameters to consider how the crew might spend 18 months conducting local and regional geologic reconnaissance and field work, and what they would require in terms of the equipment, capabilities, and skills to accomplish their goals.

The workshop participants formed four teams to address topics dealing with the surface mission, and each team presented their top-level recommendations for each. The four major themes addressed were:

1. Approaches to Mars Field Geology
2. Instrumentation: Analytical Capabilities on Mars
3. Crew Skills and Training
4. Communications Between Mars and Earth

This volume contains an introduction to the workshop and discussions and resulting recommendations from each of the four teams. A list of workshop participants and their relevant experience is also included. I would like to thank the following individuals for reviewing this document: Paul Spudis, Mike Duke, Carl Allen, Bob Garrison, Steve Hoffman, and Martin Brasier. I would also like to thank the team leaders William Muehlberger, Patricia Dickerson, Frances Westall, and Thomas Jones for leading their respective group discussions, writing the original topical reports, and reviewing early drafts of this paper. Logistics, administrative, and publications support for the workshop were provided by the Publications and Program Services Department of the Lunar and Planetary Institute. Special thanks go to Carol Howard and Angel Lopez, whose help was greatly needed and appreciated in preparing for and executing the workshop.

Nancy Ann Budden
Houston, Texas
June 1999

CONTENTS

Introduction to the Workshop **1**

Results from the Workshop Teams **5**

Team I: Approach to Mars Field Geology **5**

Team II: Instrumentation — Analytical Capabilities on Mars **15**

Team III: Crew Skills and Training **25**

Team IV: Communications Between Crews on Mars and Scientist on Earth **31**

References **37**

Appendix 1: Mars Surface Reference Mission, Stephen Hoffman, 1998: Excerpts **39**

Appendix 2: List of Workshop Participants, and Experience Relevant to Mars Exploration **59**

Appendix 3: Workshop Communications, Agenda, and Discussion Outlines **67**

Appendix 4: Strawman Science Payloads and Feasibility Study **75**

Appendix 5: Mars Mission Questions: Ralph Harvey **77**

INTRODUCTION TO THE WORKSHOP

Workshop Objectives

Current NASA planning envisions human missions to Mars as early as 2013, on a mission that would send six crew members for a 500-day stay on the surface of Mars. While our understanding of how we would get there and back is fairly mature, the planning for what the crew would do to explore while on the surface for 500 days is less detailed. Mission objectives are to understand the composition and geomorphology of the martian surface, and to continue to investigate and sample the geologic history of Mars. Special emphasis will focus on exploring for possible biogenic signatures, past or present, and on analyzing pre-biotic chemistry.

The purpose of this workshop was to explore the strategies, desired capabilities, skills, and operational realities required to lend success to the first human missions to Mars. Current mission planning dictates that there will be considerable mobility, sampling and analytical capability available to human crews, at a site warranting long-term geologic and possibly biological interest. However, the details of specific capabilities are not yet clearly defined.

Process

In order to develop a plan for what human crews would require in exploring the martian surface, the workshop process was divided into four sequential stages: First, we brought workshop participants up-to-speed on current NASA planning for Mars missions, so that everyone was using the same base-level of information for their discussions. This was done by first providing preliminary information and documents, including the Mars Reference Mission (Hoffman et al., 1997), to the participants prior to the meeting. At the meeting, NASA engineers, scientists, and astronauts gave presentations on various aspects of human missions. NASA mission planners presented the latest mission scenarios for Mars and clarified constraints and limitations. The workshop agenda is included in Appendix 3.

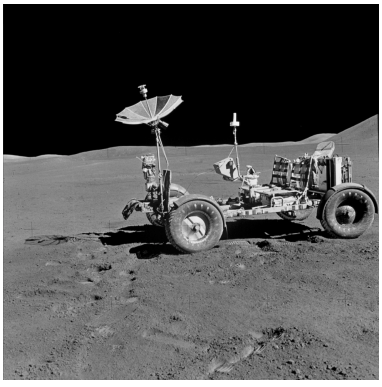
In the second step in the workshop all participants were engaged in a series of discussions focusing on four themes. Four discussion team leaders led the discussions, keeping them on target and within time constraints. Outlines of the discussions were developed before the workshop to guide and focus discussions, and to provide a template for the final product, a written report. These discussion outlines are included in Appendix 4. The third stage was to break into groups to accelerate discussions with smaller teams, and to generate recommendations. The final part of the process took place after the workshop, and entailed writing up the results of the four discussions.

The four discussion themes with associated questions were:

1. Approaches to Mars Field Geology
What should the exploration strategy be in the field? Are there significant differences between geological and paleontological field work? What tools are needed? What prior information must be gained/assumed?

2. Instrumentation: Analytical Capabilities on Mars
What observations and measurements do we need to make on Mars? What kinds and levels of analytical capabilities are needed in the field to make these measurements? In the laboratory? How should work in the field and work in the laboratory be coordinated? Which preliminary analyses are done on Mars?

3. Crew Skills and Training
What scientific skills are needed? What training environments are most important? What techniques for maintaining skills seem most important?



4. Communications Between Mars and Earth
What is the desired level of autonomy of crew members on Mars? What should be the principal objectives for communication between astronauts on Mars and scientists on Earth? What are the impacts of the forty-minute time lag? How do we handle pre-mission science planning vs. real-time changes in exploration strategy?

Fig. 1. Geologist and astronaut Jack Schmitt sampling impact breccia boulder at Taurus Littrow, Apollo 17.

Invited Participants

An additional major objective of the workshop was to bring together a unique mix of disciplines, skills, experience bases, and cultures within both the Earth science and aerospace communities with a common goal in mind: to consider what it would take to explore the surface of Mars with humans. Owing to the very focused goal of the workshop, individuals were invited to participate based on their specific qualifications. Members of the science community were invited on the basis of their past field experience on Earth or the moon, along with their expertise in laboratory analyses and instrumentation, and included field geologists, stratigraphers, paleontologists, microbiologists, geophysicists, geochemists, and astronaut trainers. The attendees included two Apollo astronauts who had done field geology on the lunar surface, and several of the geologists who trained them. Shuttle and future International Space Station astronauts attended, along with Mars mission planners, a JPL/Mars Pathfinder scientist, and space flight management from NASA Headquarters. One participant was a field geologist who is presently a test

subject for the latest Mars space suit, currently under consideration at the NASA Johnson Space Center EVA Office.

A list of workshop participants, their addresses, affiliations, and a brief biography for each individual is summarized in Appendix 2.

Baseline: Mars Reference Mission

The baseline for discussion during the workshop was the Mars Reference Mission (*Hoffman et al.*, 1997). It was necessary that participants have a common datum for developing their ideas on field campaigns, outfitting the Mars base laboratory and exploratory rovers with scientific instruments, and partitioning skill requirements among the crew members. To do this, we had to have a common understanding of what the mission capabilities and constraints were. This reference document can be located on the World Wide Web at the following addresses:

http://exploration.jsc.nasa.gov/EXPLORE/explore.htm

or

http://www-sn.jsc.nasa.gov/marsref/contents.html

In addition to the Mars Reference Mission, we used new information recently compiled in a document called The Mars Surface Reference Mission (*Hoffman*, 1998). This report deals specifically with the mission on the surface of Mars. It sheds light on the more detailed objectives of a 500-day surface mission, and the strategies and activities required to implement these goals. Pertinent excerpts from this document are included in Appendix 1.

Mars Science Objectives

Workshop participants were also presented with the science objectives for Mars exploration that have evolved over the past decade from workshops and conferences. Table 1 shows these science questions (after *Hoffman*, 1997).

TABLE 1. Science questions for Mars exploration.

Science Questions for Mars Exploration
• Did the climate change on Mars from warm and wet to a frozen desert, and if so, why?
• Has life ever existed on Mars, and if so, does any life exist there now?
• How did Mars evolve geologically?
• What is the resulting inventory of resources on Mars?

RESULTS FROM THE WORKSHOP TEAMS

TEAM I: APPROACH TO MARS FIELD GEOLOGY

William Muehlberger (team leader), Jim Rice, Tim Parker, Jere Lipps, Paul Hoffman, Clark Burchfiel, and Martin Brasier

Fig. 2. Dean Eppler sampling volcanic material in 1998 Arizona field test of Mark III Mars EVA suit.

Premise

The goals of field study on Mars are nothing less than to understand the processes and history of the planet at whatever level of detail is necessary. A manned mission gives us an unprecedented opportunity to use the immense power of the human mind to comprehend Mars in extraordinary detail. To take advantage of this opportunity, it is important to examine how we should approach the field study of Mars. In this effort, we are guided by over 200 years of field exploration experience on Earth as well as six manned missions exploring the Moon.

1. APPROACH AND STRATEGY

We recommend that the six astronaut crew members contain a strong team of experienced Earth scientists. For example, we envisage a crew of two geologists plus a paleontologist with considerable field experience. Between them, these individuals may have cumulatively upwards of 30 years experience in ter-

restrially based field science. We also envisage that the other three crew members will have been cross-trained in some aspects of the Earth sciences. This assumption has major implications for the astronaut training program.

Strategies adopted for field work on Mars are likely to vary between successive missions. Early missions may focus more upon engineering and stabilization of mission systems, establishing safety protocols, developing the infrastructure of the base and field areas, and on reconnaissance. Later missions may target particular scientific problems identified during the early missions and have a greater portion of the surface stay focused on field work.

2. SITE SELECTION

Approaches to field work on Mars may be at least partly site-dependent. It is assumed that a handful of possible landing sites will be studied from orbit and explored by unmanned rovers at the candidate sites before the final site for landing humans is picked. We assume that safety and resource potential will play a role in site selection, thus, the chosen site must maximize the possibility of solving as many of the basic problems of martian geological, climatological, and biological evolution as possible. In other words, it must have a variety of geologic features and terrains in proximity, available for study.

We identified several major questions that should be addressed:

1. What is the geological history of Mars? What are the ages of the major martian events?
2. When did early heavy bombardment cease?
3. How long did major volcanism continue?
4. What was the source of water for the major flood events and when did they occur? Were they catastrophic or longer term? When did the floods occur? Where is that water now?
5. How did the atmosphere evolve? What was the climatic history? Was there a change in climate from warm-wet to cold-dry? If so, when did each climate exist? Did Mars experience greenhouse effects?
6. Were there any habitats potentially suitable for life on Mars, such as lakes, oceans, and hydrothermal springs? If so, when did they exist?
7. Is there any evidence for life on Mars, past or present?

3. PRE-MISSION ANALYSIS

Once a site is selected, it should be studied in as great a detail as possible using both orbital remote sensing and unmanned surface rovers to locate key outcrops, regions for ground study, and places to drill. To assure maximum science return in case of abort, traverses must be designed to reach the most significant localities as early as possible in the EVA sequence.

4. EARLY ROBOTIC RECONNAISSANCE

Because of the six month flight to Mars, the astronauts will require some time to acclimatize to martian gravity. While the crew is recovering, they can initiate three phases of robotic reconnaissance: biohazard reconnaissance, resource evaluation, and terrain potential.

A. Biohazards and toxicity reconnaissance

Before the astronauts can leave the safety of the lander, or bring back samples to the habitat, they will need to conduct simple tests to demonstrate that the immediate environment of the habitat is biologically inert, i.e., that it does not present hazards in the form of pathogens, and that it is free from life-threatening toxins. These tests could be carried out by an unmanned rover.

B. Resource evaluation reconnaissance

The potential of the landing site to yield important resources such as water, H_2O ice, geothermal energy, natural shelters, and building materials, will need to be assessed. If present, water will provide a vital resource that can augment reserves brought from Earth. It can also be electrolyzed to make hydrogen and oxygen. The search for water/ice will involve determining its depth, and its potential for being mined. Tests for water could be carried out by means of ground penetrating radar situated on the lander or on an unmanned rover. Deep drilling for water should be initiated as early as feasible in the exploration effort, for possible use during the remainder of the mission. Sediment substrates suitable for the support of crop growth should also be identified early on in the mission.

C. Terrain reconnaissance

During this initial exploratory phase, the astronauts can undertake a robotic reconnaissance of the immediate landing site, driving unmanned rovers with telepresence cameras to selected rocks, features, and nearby hilltops to get a view of what lies over the horizon. Rovers could additionally deploy communication repeaters, navigation beacons, and environmental monitoring equipment. The rovers, if equipped with tongs, could pick up selected rocks and bring them to the lander where they would be inserted into the outer side of a glove box for inspection by the astronauts from the inside. These initial collections would constitute a minimal contingency sample.

Data from this initial robot reconnaissance will refine the initial EVA traverse sites. Identified problems will determine objectives and sampling techniques (collecting via hammer, rake, core tubes, etc.) of the initial EVAs. These rocks should then be taken to the lander for analysis (classification by type, process, analysis for chemistry, mineralogy, isotopes, comparison with remote sensing data, and compilation and updating of the preliminary geologic map of the site). These samples could then be split and stored as an emergency contingency sample.

5. EQUIPMENT TESTING

For the first few days of astronaut activity outside the lander the astronauts will need to pay close attention to equipment and human performance under martian conditions, thereby validating tests and information derived from previous robotic missions and Earth-based testing. For example, will the very fine dust of the martian atmosphere affect the suit? Will the gloves work satisfactorily? How is the human metabolic rate affected by various activities?

6. EXTRAVEHICULAR ACTIVITIES (EVAs)

It is assumed that there will be two pairs of field crews, each provided with a fully equipped unpressurized rover. One pair of astronauts will go on EVA at a time. The other pair will stay at the habitat doing laboratory studies, or visually (or via radio link) supporting the EVA pair. They will then change places for the next EVA. Those in the habitat will also be involved with maintenance duties or with manipulating unmanned rovers to explore regions not yet visited by humans.

The first EVAs should be walking traverses (up to a few kilometers) radially out from the habitat. Voice-recorded observations, digital photography, and collected samples would provide a more complete reconnaissance sample. These materials should be studied in the habitat to update the geologic map of the landing site and modify the succeeding rover traverses. Geologic tools to be used in the field are included in the section on Instrumentation — Analytical Capabilities.

Field geology is a slow and evolving process. If new discoveries do not fit with predictions of the working hypothesis, then the latter needs to be modified so that it will predict what will be found at the next stop. If these predictions come true, then confidence in that working hypothesis increases. Eventually, after all data is synthesized into the traverse, a “final” geological evolution of the site can be developed.

Field geology in a space suit is an even slower process. A geologist on Earth typically will reconnoiter a site, take a few photographs, record his observations in a notebook, break some rocks open, inspect each with his hand lens to determine the texture, structures, and mineralogy of the sample so that he can give it the correct name, and collect those samples that seem diagnostic of the locality as well as any “odd” samples. In a space suit most of these tasks will take longer or will be impossible to do (write notes, for example) so that these tasks will need to be accomplished by other means. The taking of notes can be accomplished by voice-activated machines that can transcribe the words via a computer into a visual display in the visor, on the arm, in the rover and in the habitat. A large magnifying lens mounted on the rover could substitute for a handheld device. An electronic hand lens (e.g., a magnifying fiber optic camera) could be manipulated by hand against an outcrop. For scanning a cliffside outcrop, a remote-controlled camera mounted on the rover could pan across the outcrop or zoom in for detailed views.
The camera could be controlled either from the habitat or by an astronaut at the outcrop with a small handheld screen. Information from steep, hostile, or inaccessible terrain could also be gained from remote-controlled aerobots.

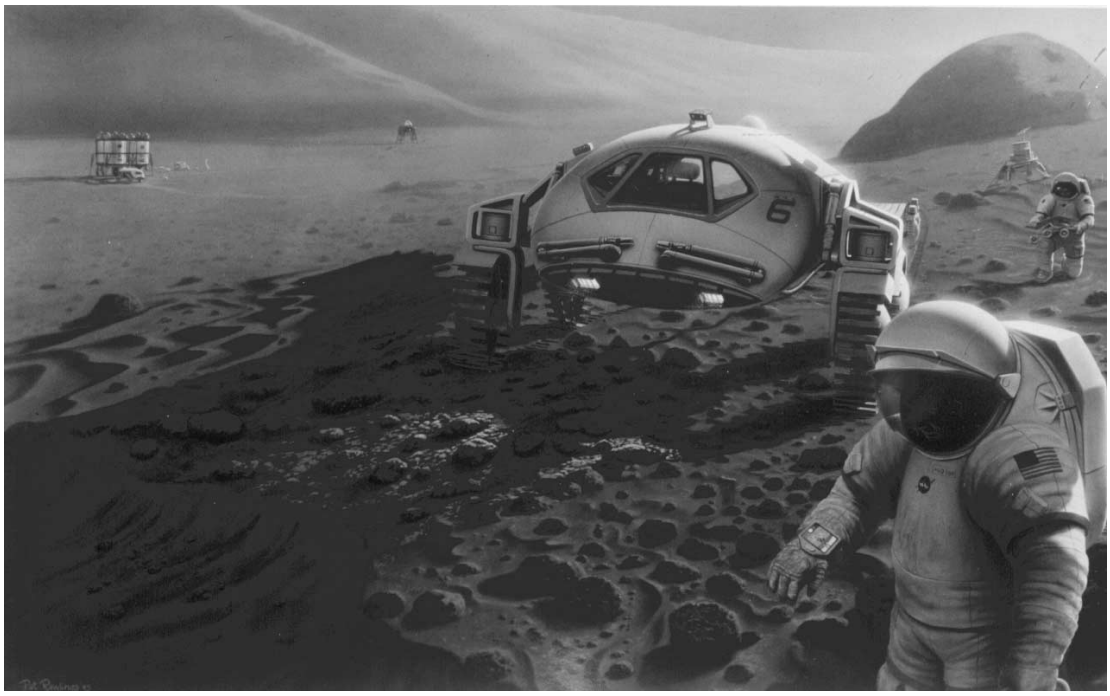


Fig. 3. "Distant Shores," by Pat Rawlings.

7. INTERMEDIATE-STAGE RECONNAISSANCE

These early EVAs should then be extended outward using manned rovers to the limit of a single days' traverse. They may be out-and-back (viewing from another direction and with different lighting might highlight a feature that was overlooked or was unimpressive on the way out); or they may be big loops (in an attempt to cover as much territory in a given EVA as is possible). Presumably, in these early traverses, only surface samples or hammer cores will be taken. Deep drilling may follow the surface exploration. Traverse geophysics should be an integral part of this series of EVAs — while traversing, subsurface seismic data could be collected and later correlated with observations and collected samples to describe the regional geology.

Unmanned rovers can be used to explore ahead of and beyond the limits of manned rover traverses. Unmanned rovers with electronic cameras can furnish information on surface morphology (e.g., layering, rocks, sharp changes in elevation) beyond the ranges possible with manned EVAs.

Laboratory studies should progress along with the EVAs. This might require free days during which no EVAs are scheduled. Workloads need to be carefully considered for the long-duration stay of this mission option.

8. SYNTHESIS TIME

A logical stopping point for this phase of exploration would be after all targets within the one-day EVA range have been visited. This will allow both the Earthbound scientists and Mars astronauts to synthesize together what has been learned. Only then can the design of extended traverses using rovers capable of supporting life remote from the home habitat begin. The landing site will undoubtedly have pre-mission

targets already known that are beyond the range of day trips, but the sequence of exploration can only be fixed after careful study of the immediate landing site (e.g., 10-km radius?)

It is assumed that the reconnaissance traverses outlined above will take about one-quarter of the available surface time, that is, 25% of 500 days (125 days), or about 4 months.

9. EXTENDED EVAs

Reviewing these accomplishments will set the framework for the more arduous, extended (days, weeks?) traverses with a mobile habitat for the pair of astronauts involved. There may also be important sites for deep drilling to explore for stratigraphic information, possible life and water.

This aspect of the exploration of the site can not be done prior to the synthesis of the traverses already completed to this point. Certainly there will be remote localities that are known prior to landing that will be candidates for manned exploration. There will also be interesting sites identified during the course of this early reconnaissance, as well as areas that the astronauts will need to return to for further study. And more often than not, the earlier localities that were initially visited will need to be revisited in the light of the new discoveries made on this exploration.

Once the martian and Earthbound scientists agree on target priorities, then traverses can be designed to most effectively explore the regions more remote from the Mars base habitat.

10. SAFETY PROTOCOLS AND STRATEGIC PLANNING

The EVAs, and especially the extended EVAs, will require carefully developed safety protocols and contingency plans. Indeed, their design is likely to depend upon certain protocol requirements being met; for example, agreed distances, speeds, avoidance of known hazards, route to be taken, levels of natural lighting, visibility, dust storms, frost, inclines. These questions will be critical for areas with steep cliffs, soft ground, or other natural hazards. Contingency plans should be drawn up between the field crew and the base crew before the EVA commences. The following situations will need to be considered (the list is probably incomplete!):

- space suit malfunction
- manned rover malfunction
- malfunction or loss of communication between field crew and home base
- immobilization due to dust storms (weeks, months?)
- degradation of temporary habitat
- exhaustion, dehydration
- sickness or injury

During the first mission, we assume that there will be one rover in reserve at the lander, and one on EVA. The reserve rover will need the capacity to carry two astronauts from the base to rescue two astronauts on EVA. The safe return of their vehicles to base will be important at this stage. In later missions, more rovers will be available, allowing greater flexibility for rescue and maintenance.

Given that there is likely to be more than one mission to an area, and that the plan is to build up resources over a period of time, then extended EVAs could also include an element of strategic planning. Supplies of water or other vital resources can be left at strategic outposts. Aerobots or unmanned rovers could be involved in this strategic deployment of resources. In this way, the resources for one or more outposts can be built up for future intended or emergency use during the later stages of exploration.

Fig. 4. 1998 field traverse in Arizona testing the Mark III Mars EVA suit.

11. MARS SUIT IMPROVEMENTS

A repeated theme in this workshop was the requirement for improved suit technology, design and performance. Particular emphasis was placed on improving glove dexterity, flexibility, and performance. In addition, it is assumed that space suit design will provide the capabilities and tools to accomplish tasks necessary for geologic field work. For example, we need a system of electronic field notebooks, perhaps using voice-activated recorders with visual display inside the visor, and relayed to printers in the habitat. Field locations will need to be fixed by means of GPS or other location system, which can be displayed as a map inside the visor or aboard the rover.

At present, the International Space Station Program is driving improvements in glove technology to support the increased EVA rate on ISS. The present Series V gloves are being replaced with Series VI gloves, which were tested by Dean Eppler in a series of crewmember/rover tests in February 1999. Eppler's experience with these gloves was extremely encouraging. In five suit runs over four days, he experienced none of the hand/forearm pain and fatigue that was experienced on the Apollo program. The

improvements seen in these gloves show that we are well on the way to solving the glove/hand fatigue problem.

Suit improvements are also being evaluated with three candidate suits. One of these suits, the Mark III or H-1 suit, has already been evaluated in the field as part of the May 1998 exercises in Flagstaff, Arizona. During two weeks of exercises, Eppler found that this suit has the level of mobility necessary to conduct field geology and paleontology on a planetary surface, in spite of the rather excessive weight (approximately 95 kg with a life support backpack). In addition to this suit, the ILC Corporation has developed a soft suit with hard bearings at the hip, shoulders, and wrists. This suit weighs approximately 35 kg without a life support backpack, and offers a reasonable level of mobility given that it has only a two-bearing hip and no wrist bearing. This suit was evaluated in the February 1999 exercise in California, and was found to be adequate, although the reduction in suit weight lead to some compromises in load-bearing strategy that Eppler felt nullified the weight loss when compared to the Mark III suit. Lastly, the David Clark Company has developed a totally soft suit that is now undergoing initial evaluation. The advanced EVA development group at JSC expects to have a complete evaluation report comparing all three suits finished in 2000.

A parallel effort is underway to develop a suite of geologic tools for future Mars and lunar exploration. Initial activity has focused on developing a complement of tools that have been used already in the two previous field exercises. This work has given the advanced EVA development group ideas for an improved suite of tools, to be developed in 1999 and 2000. In particular, a new reach-and-grasp tool needs to be developed to handle samples in the size range of 10–30 cm, as well as a new scooping tool for soil sampling.

TEAM I: RECOMMENDATIONS — APPROACH TO FIELD GEOLOGY

Fig. 5. "Day Hike in Dao Valley," by Pat Rawlings.

1. **While the crew is acclimatizing to gravity upon landing, robots should be used to reconnoiter the site, to confirm that it is free of biohazards and toxins, and to bring selected rocks back to the base for study in glove boxes accessible to the robot on the outside and by the astronauts from the inside.**
2. **Only 2–3 astronauts should be on an EVA at any given time, so that if necessary, crew remaining at the Mars base can rescue them. Safety protocols will need to be developed.**
3. **Traverses should be designed with considerable latitude in time allocation and the number of projects to be completed at a given locality.**
4. **Traverses should increase in complexity as both skills and confidence increase.**
5. **Initial walking traverses should be targeted on sites of the highest priority sites identified to date.**
6. **Upon completion of walking traverses from base, the Earth and Mars teams should design a set of extended traverses for the next phase of research.**
7. **Geophysical studies of the landing site should begin at the earliest opportunity to determine if water or other resources might be present at achievable depths.**
8. **Advances in Mars suit and glove technology and design are imperative.**

TEAM II: INSTRUMENTATION — ANALYTICAL CAPABILITIES ON MARS

Frances Westall (team leader), Carl Allen, Martin Brasier, Jack Farmer, Wulf Massell, Andrew Steele, Russ Fortson, and Carl Agee

Fig. 6. Astronaut Buzz Aldrin carrying a lunar instrument package away from the lunar lander, Apollo 11.

Premise

Human exploration of Mars will consist of a series of long-term missions, with early missions focusing upon establishing the Mars base, and undertaking basic field reconnaissance. A capable laboratory on Mars is an essential element in the exploration strategy. Analytical equipment both in the field and in the laboratory serves to extend the senses of the crew and help them sharpen their sampling skills as they learn to recognize rocks in the field and understand their geologic context and significance. On-site sample analyses allow results to be incorporated into evolving surface exploration plans and strategies, which will be developing in real-time as we learn more about Mars.

Early Mars missions will focus on reconnaissance EVAs to collect rock and soil samples, maximizing the amount of Mars material returned to Earth. Later missions will be increasingly devoted to both extensive field campaigns and laboratory analyses. The capabilities and equipment described below will be built up at the Mars base incrementally over many missions, with science payloads and investigative infrastructure being partitioned among launch opportunities.

This discussion considers what we require to measure, observe, and explore on a new planetary territory. Alternatively, what do we need to know and how do we equip ourselves to provide ample capabilities to acquire these data? Suggestions follow describing specific instruments that we could use. Appendix 5 lists a strawman science instrument payload, and a feasibility study of equipment transportation into the field on pressurized or unpressurized rovers.

1. BASIC STRATEGY

The strategy for field work on Mars can be broken down into applied and basic science questions: (1) the identification of materials useful for life support, propellant, and construction (e.g., hydrogen, oxygen, nitrogen, phosphorus, potassium, magnesium, iron, etc.) and an evaluation of their global distribution; (2) the study of the evolution of the geology of the planet, its atmosphere, and possibly life, as well as the identification of potential sites for establishing bases and exploration. To answer both applied and basic science questions requires observations, measurements, sampling and analysis of martian material, and surface and subsurface geophysical studies.

The Mars exploration strategy relies on robotic reconnaissance followed by human fieldwork and preliminary laboratory studies. More sophisticated detailed analyses of carefully selected samples will be done on Earth. The purpose of analyzing samples on Mars is twofold. First, it is imperative to high grade martian samples such that the best and most representative ones are sent home with the crew. Second, knowledge gained from analyses done at the Mars base will enable Earth and Mars-based scientists to amend their science strategies and possibly refocus exploration efforts on particular geologic targets. The instrumentation that we take to Mars should be aimed at accomplishing these two objectives.

1. Understanding the samples — what observations and analyses will best aid the crew and Earth-based scientists to characterize the samples for life, past environments, resources, and planetary evolution?

2. High grading Mars rocks — how do we best characterize and select samples to send back to Earth? Grading the rocks will depend upon the science questions being asked, for which an understanding of the samples is imperative.

2. INSTRUMENT REQUIREMENTS

Most of the instruments discussed in this chapter have counterparts that either have flown in space, or are scheduled to fly in space, or have been developed for future missions (see *Meyer et al.*, 1995; *Hoffman,* 1998; *Budden,* 1994.) For long-duration Mars missions, it will be desirable to use instruments such as these that require:

- Low mass and volume
- Low power
- Rugged construction
- High reliability
- Safe operation

However, a few of the instruments discussed below are state-of-the-art, sophisticated analytical tools currently used in modern laboratories. Their current configurations may not be conducive to the strenuous requirements of a Mars surface laboratory or a Mars field expedition, or they may impose power or maintenance requirements on the mission that cannot be met. They are included as candidate instruments for several reasons. First, they are the best available Earth-based tool for accomplishing the exploration or observational objective. Second, by including them as candidate payloads, it serves to challenge and drive technologists to render them “mission-ready” for use on Mars, thereby meeting the durability, reliability,

and low mass/volume requirements. Third, by including these modern instruments it allows us to project the human Mars science mission into the future framework of 2013, when we are likely to have made significant advances in scientific instrument development.

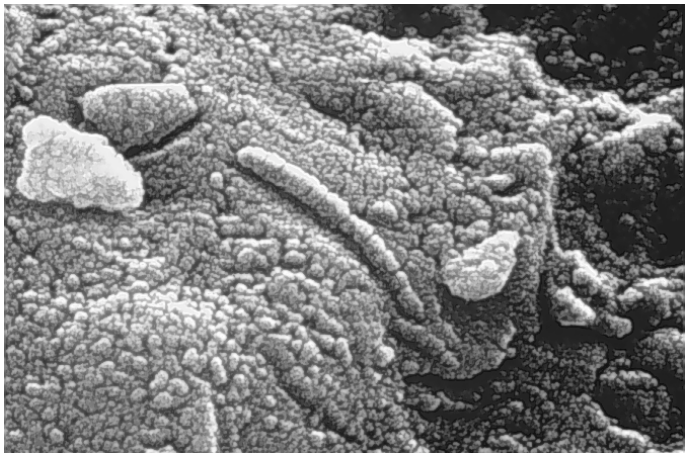


Fig. 7. Scanning electron micrograph of possible fossilized bacteria in Antarctic Mars meteorite Allan Hills 84001.

3. INSTRUMENTATION FOR SPECIFIC EXPLORATION OBJECTIVES

This section identifies six specific objectives in the human exploration of Mars, together with the analyses needed to fulfill the objectives and candidate instrumentation required for the analyses. The six exploration objectives are:

1. Field observation
2. Sample acquisition
3. Maintenance of crew health and safety
4. Search for evidence of past or present life
5. Geological and geophysical field studies
6. Sample selection and preparation

Tables 2.1 through 2.6 address the science exploration questions:

What do we need to know? (What is the science question?)
What measurement or observation will supply the answer?
What instrument can make that observation or measurement?

TABLE 2.1. Objective 1: Field observation.

Analysis	**Candidate Instrument**
Observation	Camera/hand lens/in-visor screen
Recording	Digital field note book/voice recorder
Location	x,y,z system
Soil/rock composition	Mineralogical/organic sniffer (Alpha-Proton X-ray spectrometer/gas chormatograph-mass spectrometer, magnetometer)
Environment	Environmental microprobes Oxidant detector Weather gauge
Biology	Life detection unit

TABLE 2.2. Objective 2: Sample acquisition.

Task	**Candidate Instrument**
Sample acquisition	Robot/rover Scoop/mole/corer/drill/hammer
Sample containment	Bar-coded sample bags (sterile for biological samples) Sample containers (sterile for biological samples)

TABLE 2.3. Objective 3: The maintenance of crew health and safety.

A. Investigating soil toxicity (laboratory):	
Analysis	**Candidate Instrument**
Particle size	Optical (light and binocular microscope)
Major elemental composition	X-ray fluorescence spectrometer
Mineral composition	Raman spectrometer UV/visible/IR spectrometer X-ray diffractometer
Evolved gas	Furnace/mass spectrometer
Radioactivity	Geiger counter

B. Investigating microbiology (laboratory):	
Analysis	**Candidate Instrument**
Biosafety	Glovebox
Observation	Fluorescent microscope Confocal microscope Scanning electron microscope Atomic force microscope
Organic chemistry	Gas chromatograph-mass spectrometer
Replication of live specimens	Polymerase chain reaction sequencer

TABLE 2.4. Objective 4: The search for evidence of past or present life.

A. Identification of prime sites (orbit and field):	
Analysis	**Candidate Instrument**
Location	High-resolution digital camera
Image analysis and mapping	Global information system

B. Biosafety:	
Analysis	**Candidate Instrument**
Biological safety	Glovebox

C. Rock identification (field and laboratory):	
Analysis	**Candidate Instrument**
Basic composition and fabric	Visual observation/field lens/field microscope Optical (light and binocular) microscope
Major element composition	X-ray fluorescence spectrometer
Mineral composition	Raman spectrometer UV/visible/IR spectrometer X-ray diffractometer

D. Biomarkers (laboratory):	
Analysis	**Candidate Instrument**
Organic chemistry	Gas chromatograph-mass spectrometer
Microfossils	Optical microscope Scanning electron microcope Atomic force microscope

E. Living microorganisms (laboratory):	
Analysis	**Candidate Instrument**
Observation	Fluorescent microscope Confocal microscope Scanning electron microscope Atomic force microscope
Organic chemistry	Gas chromatograph-mass spectrometer
Gas evolution	Labeled release experiment Gas chromatograph-mass spectrometer
Replication	Polymerase chain reaction sequencer
Cryogenic storage	Cryocooler

TABLE 2.5. Objective 5: Geological and geophysical field studies.

A. Geologic history (laboratory):	
Analysis	**Candidate Instrument**
Location	Orbital imaging/analysis system
Image analysis and mapping	Global information system
Correlation of strata	High resolution digital camera

B. Rock identification (laboratory):	
Analysis	**Candidate Instrument**
Basic composition and fabric	Visual observation/field lens/field microscope Optical (light and binocular) microscope
Major-element composition	X-ray fluorescence spectrometer
Mineral composition	Raman spectrometer UV/visible/IR spectrometer X-ray diffractometer

C. Geophysical measurements (field):	
Analysis	**Candidate Instrument**
Stratigraphy	Seismic exploration instruments
Rock/ice/water interfaces	Seismic exploration instruments Radar
Gravity	Gravimeter
Magnetics	Magnetometer

TABLE 2.6. Objective 6: Sample selection and preparation for return to Earth.

A. Geologic samples (field and laboratory):	
Analysis	**Candidate Instrument**
Basic composition and fabric	Visual observation/field lens/field microscope Optical microscope
Biomarkers (organic and fossil)	Gas chromatographer-mass spectrometer Optical microscope Scanning electron microscope Atomic force microscope
Martian conditions	Cryo-cooler
Major element composition	X-ray fluorescence spectrometer
Mineral composition	Raman spectrometer UV/visible/IR spectrometer X-ray diffractometer

B. Biological samples (field and laboratory):	
Analysis	**Candidate Instrument**
Observation	Fluorescent microscope Confocal microscope Scanning electron microscope Atomic force microscope
Organic chemistry	Gas chromatographer-mass spectrometer
Gas evolution	Labeled release experiment Gas chromatograph-mass spectrometer
Replication	Polymerase chain reaction sequencer
Cryogenic conditions	Cryo-cooler

4. ADDITIONAL INSTRUMENTATION: ROVERS AS FIELD EXPLORERS

Fig. 8. Future Mars crew member recovers the Sojourner rover from Mars Pathfinder mission. Painting by Pat Rawlings.

A. Robotic reconnaissance/first analysis rover

A robotic reconnaissance/first analysis rover has two uses: (1) to test for the presence of life in and around the landing site; (2) to do preliminary reconnaissance and analyses in the time period immediately after landing when the field crew needs to acclimatize itself and will not be ready for EVAs.

The reconnaissance/first analysis rover could be equipped with the following instrumentation (based on the recommendations of *Brack et al.*, 1998):

- panoramic camera for general view of the landing site, base site;
- balloon with camera/location unit;
- life detection instrumentation (labeled release experiment plus GCMS);
    - sterilized scoop/mole, sterilized sample containers, temperature control for biological sample collection
    - scoop, mole, drill plus containers for mineralogical, palaeontological and biogeochemical sample collection
    - rock surface grinder for cleaning surfaces for observation and analysis
    - APX spectrometer, laser Raman spectrometer, and Mössbauer spectrometer for soil/rock geochemistry
    - oxidant detector (fibre optics kind?)
    - environmental microprobes (pH, Eh, salinity etc.)
    - x,y,z positioning system
    - environmental monitors (mini weather gauge for temperature, wind speed, humidity)

B. Unpressurized and pressurized rovers/field crew

Open rovers would be used for near-base activity, pressurized rovers could be used for long-distance activity that would involve some days away from the base. The field crew will carry with them a basic tool kit, geological and/or biological. Heavier and/or more sophisticated equipment, will be carried on the rover. The rover would also carry basic geophysical instrumentation (taking passive measurements from the moving vehicle) and environment measuring devices (for weather parameters, pH, Eh, salinity, etc.).

In summary, the geologists/biologists in the field require the following:

Geologist tool kit:	hammer, rake
	shallow coring device
	optical magnification (maybe zoom camera)/continuous camera recording
	voice activated recorder
	magnet
	(Mars compass, clinometer)
	bar-coded sample bags
	sample container
	microchip mineralogical/organic "sniffer
Biologist tool kit:	life detection unit (biochemistry on a chip)
	environmental microprobe
	sterile sample containers and sampling instruments

Additional instrumentation for longer excursions: APX

C. Aerobots

Longer distance exploration could make use of aerobots. These could be remotely-controlled by the astronaut (via telepresence) to image the surface from altitude, descend to the surface for sample collection or *in situ* analysis, deploy instruments, ascend and move on. The aerobotic exploration patterns would be largely controlled by the prevailing winds, but model simulations have been run which show a wide area of coverage within certain latitudinal constraints with many trips around the planet possible in just a few weeks. Clearly this could open up vast areas for telepresence exploration and greatly expand the scope of missions.

5. CONTAMINATION AND PLANETARY PROTECTION ISSUES

A subcomponent of planetary sampling strategy involves acquiring uncontaminated samples for exobiological (including life detection) experiments in order to demonstrate that the exploration sites are biologically inert and safe for astronauts to leave the habitat. Exobiological studies will also be required because of the major concern about forward contamination of the martian surface by astronauts. Remotely controlled robotic exploration may well be the best way to ensure the acquisition of pristine samples (e.g., during sterile drilling to explore for subsurface life).

The analysis of exobiological samples will clearly require a bio-containment facility to protect the astronauts against contamination. This could be crucial when sampling environments where life could still be active, such as deep subsurface water samples acquired by drilling. Moreover, life could even be present in geological and paleontological samples taken on the surface. All reasonable steps must therefore be taken by reconnaissance robotic rovers to determine the possible biological hazard of the site, prior to the arrival of the field crew. Clearly, such issues will be an important part of the design of the science experiments, exploration technologies and sampling protocols.

Fig. 9. Mars field geologist studies in-visor screen projection of martian fossils, magnified by hand-held microscope. Painting by Pat Rawlings.

TEAM II: RECOMMENDATIONS — ANALYTICAL CAPABILITIES

1. The need for specific observations and analyses should be the primary driver for the development of compact, integrated field instrumentation. Field exploration and laboratory work on Mars would require the development of a number of new instruments and the adaptation of other instruments already in use:

- ***a continuously recording fiber optic camera*** could be mounted on the helmet;
- ***a magnification camera*** that can be deployed by hand as a hand lens;
- ***a display panel inside the visor*** for real time observation;
- ***an electronic field notebook for data recording and archiving***. For example, an ***integrated digital system could be placed on the space suit*** and designed for accessible entry and retrieval of information;
- ***a voice recognition system***, displayed in real time on a data viewing panel inside the visor, for data recording;
- ***an in-visor map*** relating samples and outcrops to the x,y,z, data;
- ***bar-coded sample bags*** and containers that can be registered using a digital modification of the hand-lens. In this way, all digital imaging, voice recordings and sample location data could be co-registered to the local coordinate system and archived in near-real time.

2. The miniaturization of present instruments and the designing of new technologies should start now.

3. Biologists, field geologists, geochemists, and engineers should work together at all stages of mission planning.

TEAM III: CREW SKILLS AND TRAINING

Tom Jones (team leader), Dan Burbank, Dean Eppler, Bob Garrison, Ralph Harvey, Stephen Hoffman, and Harrison Schmitt

Fig. 10. Mars test suit subject and field geologist Dean Eppler overlooking Meteor Crater, Arizona, in Mark III Mars EVA suit.

Premise

One of the major focus points for the workshop was the topic of crew skills and training necessary for the Mars surface mission. Discussions centered on the mix of scientific skills necessary to accomplish the proposed scientific goals, and the training environment that can bring the ground and flight teams to readiness. Subsequent discussion resulted in recommendations for specific steps to begin the process of training an experienced Mars exploration team.

1. SKILLS NEEDED FOR SURFACE EXPLORATION AND THE OVERALL EXPEDITION

What mix of skills are needed by the expedition crew to accomplish their mission? These required skills stem from the nature of the work required on the surface, and work necessary during other mission phases (outbound cruise, surface adaptation, Mars orbit rendezvous, inbound cruise, and Earth entry). To arrive at the necessary skills, we first highlighted surface activities for the mission (outlined in the Mars Surface Reference Mission document, *Hoffman,* 1998):

Surface Activities for a Mars Mission

a. Field geology and biology investigations to address mission science goals
b. Field searches for extinct or extant martian life
c. Teleoperation of robotic sample collection systems, such as rovers
d. Preliminary analysis of samples
e. Communication of findings to science team on Earth
f. Deployment of geophysical/meteorological experiment packages
g. Retrieval of special samples, using deep-drilling, for example
h. Active experimentation on biological, geological, and environmental samples
i. Studies of Earth life forms exposed to the martian environment
j. Sample preparation for Earth return
k. Maintenance and repair of equipment

In addition, a variety of specific skills or professions would be desirable among the surface crew members. Some examples are medical personnel, nuclear engineers, geologists, exobiologists, mechanics, pilots, instrument technicians, paleontologists, chemists, and life support technicians. Significant skills cross-training would be necessary to insure mission success. The Mars Reference Mission (*Hoffman*, 1997), baselined a crew of six with the following areas of specialization:

TABLE 3.1. Crew roles: Mars reference mission.

Position	**Responsibility**
commander	Oversight/organization/prioritization
physician	Crew health
geologist	Field exploration and sampling
biologist	Field exploration and sampling
electrical/electronics engineer	Systems and instrumentation maintenance
mechanical engineer	Systems and equipment maintenance

The Astronaut Office at Johnson Space Center continues to consult with JSC's Advanced Projects/Exploration Office on new developments for the Mars reference mission. In mid-1998, the Astronaut Office conducted its own survey of space shuttle and station crew members to produce a list of the skills needed for a Mars mission. The survey ranked an arbitrary list of proposed skills in the following order of importance:

TABLE 3.2. Ranking of crew skills in Astronaut Office survey.

Skill	**Crew Role**
1. Mechanic	Systems maintenance
2. Leader	Commander/field exploration lead
3. Electronics Technician	Systems and instrumentation maintenance
4. Engineer	Systems operation and maintenance
5. Pilot	Spacecraft operation
6. Physician or Medical Technician	Crew health
7. Computer Engineer	Systems and instrumentation maintenance
8. Scientist (specialization TBD)	Field exploration and laboratory research
9. Machinist	Systems maintenance
10. Cook	Food variety (secondary skill)
11. Maid	Habitat organization (essential for all crew)
12. Journalist	Recording crew activities (secondary skill)

Note: Also considered in the survey were traits such as "saint" and "athlete." The moral qualities of a saint ranked rather high (just behind electronics technician), while athletic skills placed behind "scientist."

Our workshop group discussed the topic of crew skills extensively. Our group was primarily interested in the successful accomplishment of the field exploration task on Mars, and we emphasized scientific skills and the ability to conduct a productive field operation without convenient Earth communications. No matter what the crew size, we recommended that the Mars crew should be equipped with the team skills

and depth necessary for a vigorous pursuit of mission science goals. We envisioned two separate field teams, alternating days spent outside the outpost engaged in field work. This surface science emphasis led us to recommend that the crew have a skills ratio of roughly 2:1 in favor of surface science over the (essential) spacecraft systems and operation function. Reflecting this mix, we modified the crew skills list developed in the Reference Mission above. Our workshop strawman list of necessary crew specialties is shown in Table 3.3.

TABLE 3.3. Crew roles for Mars surface mission (this workshop).

Prime Role	**Backup Role**
Commander; Research and Operations Manager	Geologist
Geologist	Paleobiologist
Systems Engineer	Electronics Engineer/Technician
Physician or Medical Technician	Microbiologist
Geologist	Mechanical Engineer/Technician
Paleobiologist	Systems Engineer

Naturally, this crew skills mix can and should change depending on which stage of Mars exploration is underway. The earliest missions might weight their crews more heavily to operational experience, while later crews, benefiting from experience and more surface infrastructure, could focus more heavily on the surface science disciplines.

Our skills mix reflects the reality that the crew, limited in size and committed to a mission duration approaching three years, necessarily must be heavily cross-trained. Astronauts in our group stated that experience shows it is best to select a crew weighted toward the primary scientific skills for the extensive surface mission, and cross-train them to accomplish the spacecraft systems, operations, and maintenance functions. Apollo and shuttle experience shows that scientists can successfully acquire the essential mission operations skills in just a few years of spaceflight training, while the reverse process of training pilots and technicians for a primary science role will not work on a similar timescale. Geologist and Apollo 17 astronaut Jack Schmitt's estimate is that during Apollo, the scientists had acquired 75% of the operations skills of the pilots in the program, while the latter had attained 25% of the field geology skills typical of active field geologists. Our consensus was that successful cross-training can be accomplished over a period of about 10 years. That's about the timescale for development of expert operations skills via actual spaceflight experience on shuttle and space station, experience that is likely to be a prerequisite for Mars mission candidates.

Note: Our panel highlighted the value of operational aviation experience to the training of spaceflight crewmembers. Spaceflight proficiency training in high-performance aircraft should continue to be part of the long-term training for any Mars crew candidates.

Our group briefly discussed the gender and nationality mix best-suited for success on a Mars expedition. Field experience at remote sites, and our limited long-duration spaceflight experience, shows that gender mix can critically affect a crew's day-to-day interaction and thus their productivity. Rather than rely on our incomplete and anecdotal experience, any Mars exploration program must confront and understand this important human dynamic. Historical experience in the annals of exploration suggests also that we

carefully examine the implications of a multinational crew. Multicultural field teams may be at a disadvantage in survival situations, when teamwork is pushed to the limit. Thorough investigation of the gender and nationality issues must be conducted in parallel with other Mars mission preparation; in particular, we must capitalize on experience gained from crew dynamics on the International Space Station, adding that to historical and science field experience. We strongly recommend that NASA sponsor an expert workshop on this important topic.

Fig. 11. Dean Eppler testing the ILC Mars EVA suit in the California desert on a crew-rover Mars field geology simulation, 1999.

2. TRAINING EXPERIENCES AND LOCATIONS FOR THE MARS EXPLORATION TEAM

Our group reached wide agreement that field exercises for the Mars surface science mission would be essential elements of long-term crew training. Such science field trips and surface exploration exercises were very successful during Apollo in honing the field skills of both astronauts and ground science teams. We discussed many examples of current research locations and activities that could collectively deliver the necessary field experience. Some examples: geology field expeditions, petrological or geochemical laboratory experience, polar geology and other polar field programs, oceanographic voyages, paleobiological field programs, scientific drilling project legs, volcanology field sites, and eventually, multiweek stays aboard the space station or at a lunar outpost. Potential locations include Antarctic venues based out of McMurdo, the JOIDES Resolution drilling ship, the Spitzbergen Arctic research facilities, volcano and impact field sites around the globe, and paleonological Mars analogs, such as Yellowstone and the Snake River lava beds. One site that offers current easy access is Iceland: NASA flies there frequently via charter aircraft in support of its Russia-based personnel, and it offers a generous combination of the geology and polar research settings outlined above.

Many terrestrial research sites, across the spectrum of geological and paleontological disciplines, could serve as analogs for the martian surface science experience. We agreed that the successful field experience would combine real scientific work for the crew with realistic support from an integrated ground

team, so that both the science and operations communities gain experience with planning and executing an extended program of surface science. The entire team must gain experience in dealing with communications limitations, interaction between the terrestrial science support teams and the field crew, and the long-term support of a remote science program. These exercises would also provide a realistic backdrop for evaluation of potential Mars mission crew members.

3. PROPOSAL FOR EXPLORATION FIELD TRAINING PROGRAM

We see great benefits from establishing an ongoing program of scientific field exercises aimed at Mars surface exploration. Crewmembers would gain experience in managing a field research program, practice on-site decision-making, cope with changing research strategies, and develop the cross-training essential to a successful Mars mission. The engagement of support science teams and mission operations personnel would develop a vigorous exploration “culture” in the spaceflight operations community. These field experiences would also develop a cadre of “camp managers" and surface team leaders. From this cadre would come the leaders of both the Mars field teams and the Earth-based science support team.

Our group recommends that candidate Mars crews receive broad field experience over a number of years, culminating in a focused program of surface science exercises. Participation in meaningful science work, rather than mere observation, should be the goal; multiple field exercises should aim for exposure to a variety of scientific skills and disciplines, analytical as well as field-oriented. Such crews should participate in at least six full-up Mars surface science field simulations, incorporating communications delays and interactions with the Earth-based science team. Typical duration should be around three weeks, with the emphasis on scientific decision-making in the field.

The crew’s training program will reach a crescendo in the weeks prior to launch to Mars, but the cruise phase represents a possible six-month lull in scientific training. Refresher training in the skills and substance of the expedition’s surface research program should be a central part of the cruise phase outbound. Such cruise training activities might include a review of martian geological problems, in-flight analysis of Mars analog samples, and a variety of related scientific activities. For example, the crew could conduct cruise astronomy, remote sensing studies of the martian surface, and space physics investigations. These activities would continue to challenge the crew, sharpen their training, and broaden their skills using an array of equipment similar to that slated for surface deployment. During the return cruise, the crew could study in detail a subset of the collected surface samples, prepared for analysis before Mars departure.

When should this training program begin? Our panel members felt strongly that field geology is learned in the field; therefore potential crewmembers must go there as soon and as frequently as possible. It is not too early to prepare for the first Mars expedition. We should forge these links between the science, operations, and astronaut communities now. It will take time to achieve the collective experience level necessary, but it will prove invaluable in supporting and controlling a multiyear Mars expedition. As a first step, NASA should convene a workshop to capture the collective experiences and recommendations of the Apollo and Skylab crews and science support teams. These teams pioneered field exploration on the Moon and in near-Earth space, and we should record their experiences before their value is lost to the next generation of explorers.

Generic science field training for astronauts should begin now, so that the necessary field skills are in place when Mars surface science training begins in earnest. Several members of our workshop made specific proposals for astronaut participation in ongoing, active field expeditions. The workshop participants were in broad agreement that opportunities exist today for valuable Mars field exploration training, ranging from the Antarctic to remote geology and biology research camps. NASA should actively pursue participation in such field expeditions during 1999 and 2000 to pave the way for expanded, more focused field training.

TEAM III: RECOMMENDATIONS

1. The expedition crew should have roughly twice as many members with primary surface science skills over those with backgrounds in spacecraft systems and operations.

2. Mars crew training should culminate in an extensive program of realistic field exploration simulations. The crew, operations, and science support teams should participate in at least six of these field exercises before launch.

3. NASA should begin in 1999 a field training program for astronauts, mission operations, and science support teams, aimed at gaining experience in surface science operations.

4. NASA should convene new workshops on (a) crew selection, including crew skills and other pertinent criteria; (b) field science exercise site selection; and (c) recording the collective experience of the Apollo and Skylab crews, science support teams, and missions operations personnel.

TEAM IV: COMMUNICATIONS BETWEEN CREWS ON MARS AND SCIENTISTS ON EARTH

Patricia W. Dickerson (team leader), Nancy Ann Budden, Jack Frassanito, Paul Keaton, David S. McKay, and Paul D. Spudis

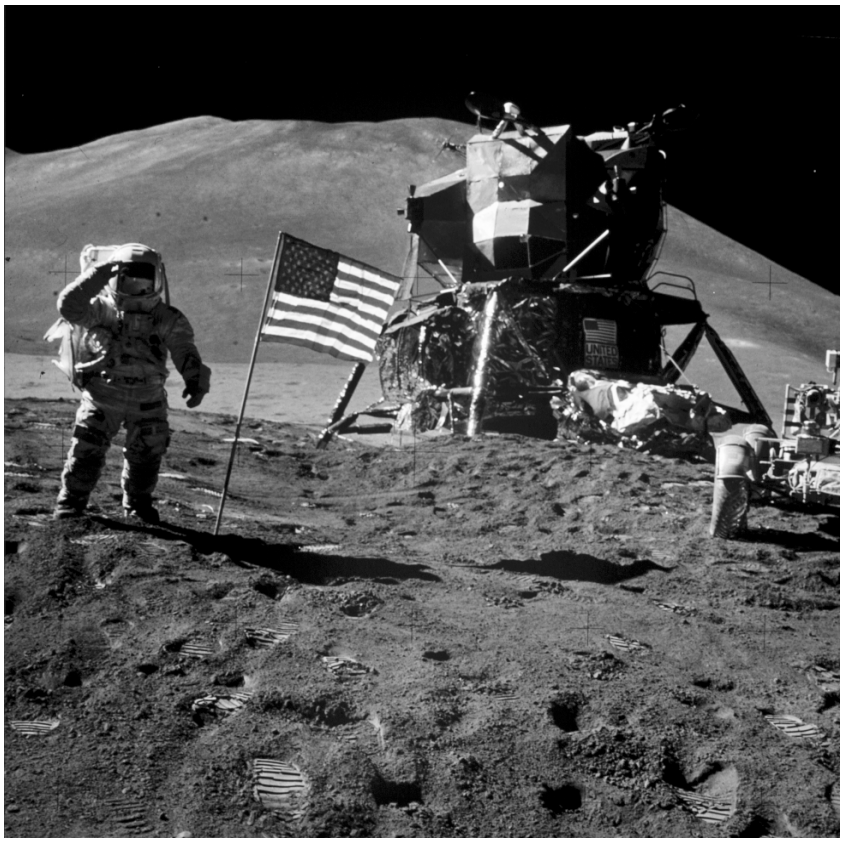


Fig. 12. Jim Irwin gives a salute from Hadley Apennine, Apollo 15.

Premise

For the purpose of the following discussion, we assume that of the six crew members sent to Mars, at least three will be scientists. We further assume that geological and biological investigations will proceed together (although investigative techniques may vary), both for vestiges of ancient life, and for evidence of living organisms. Finally, unexpected discoveries may cause sudden changes in exploration strategies, and mission planning should be flexible enough to accommodate such shifts.

1. APOLLO EXPERIENCE

Investigations of Earth's Moon during the Apollo missions represents our sole previous experience in human planetary field exploration. Apollo taught us valuable lessons, not only in setting strategy and in data and sample collection, but also in structuring effective dialogues between the explorers and scientists on Earth. However, on Mars missions, communication between astronauts and Earth support teams will

by necessity be very different from the Apollo model, due to the extended stay time, and distance-induced communications lag.

Communications technology has evolved dramatically since the Apollo era, and we assume that developments will be made before the first human mission to Mars time. Technology for data compression and transmission will have evolved to permit rapid transfer of large volumes of data, such as geophysical surveys. Robotic missions will precede human exploration and some, such as the proposed Ariane mission in 2005, may offer the potential for putting navigation and communication satellites in orbit around Mars. Such satellites could enable continuous contact between crews at the Mars base and in the field.

In contrast with lunar exploration, many or most sites on Mars will have been reconnoitered robotically and samples analyzed before humans arrive, providing a fair picture of the landing sites before humans ever step onto the surface

2. SCIENTIFIC INVESTIGATIONS — STRATEGY AND PLANNING

The 500-day stay on Mars will be the longest planetary surface exploration opportunity ever experienced. Once on Mars, human crews will benefit from the extended stay on the surface by enjoying more time in the field, more time in the Mars laboratory to examine/analyze samples and consider their findings, and the capability to return to sites of interest as field relations become better understood. There will be more time to think about the geologic setting and the context of any given sampling site, and more time to alter or abandon one line of thinking in favor of a more informed hypothesis. It is imperative that human crews have much more autonomy and flexibility than during the Apollo, shuttle, or International Space Station missions. Exploratory research plans will need to be dynamic and accommodate shifts — possibly abrupt — in strategy, focus, and/or technique.

During the early reconnaissance phases of the Mars mission, communications between the crew and Earth will be more structured and more frequent, and less so during later phases of investigation. Crew members, at least half of whom are assumed to be scientists, and the Earthbound scientific team will have an ongoing collaboration regarding the exploration strategy. Throughout the mission, rotating teams of research specialists on Earth will be on call and responsible for specific exploration segments and/or disciplines. They will be in regular contact and would respond immediately in the event of significant discoveries (the “Eureka!” experiences) and unanticipated events. Data transmitted to Earth will be monitored and interpreted by the Earthbound experts, who will collaborate on modifying the maturing field and analytical strategies based upon evolving interpretations. Team members on Earth will synthesize and report to the crew any relevant new publications and discoveries in their respective disciplines.

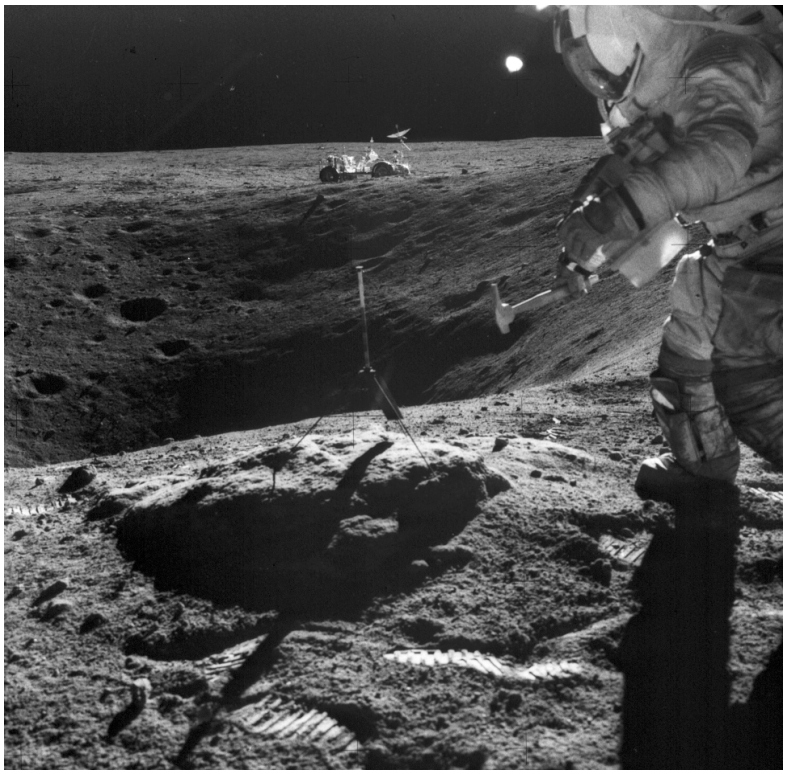


Fig. 13. Astronaut John Young wields geologic hammer at rim of Plum Crater, Descartes, with lunar rover in background, Apollo 16.

3. REAL-TIME INVESTIGATIONS AND REPORTING

One-third of the crew (two astronauts) will be in the field at any one time, while the others remain at Mars base carrying out the geological/biological laboratory analyses, conducting other scientific experiments, and maintaining the rover(s), habitat, and life-support systems. Crew members will likely alternate on field expeditions, with sufficient time between excursions for thorough discussions of observations from the field and analytical results from the lab.

Voice-activated recorders will be used to capture field observations and interpretations (that distinction would be maintained), which will be sent back to the Mars base for interpretation, for back-up in some fail-safe format, and for transmission to Earth. Field and base crews will be in daily (or more frequent) contact, and a crew member at the Mars base will serve as CapCom in discussions between the field party and the science team on Earth.

Crew briefings for the Mars science team will be conducted daily in the early stages of field exploration. As sample collection and analytic work progress and the data are assimilated, briefings may be less frequent — perhaps weekly or biweekly. Research scientists on Earth will, in turn, brief the crew weekly (or more often, as warranted) on the results of analyses and interpretations of data transmitted from Mars.

For investigations in which large digital data files are collected — such as seismic-reflection profiles — the data will be batched, compressed, and electronically transmitted to Earth for processing, review, and preliminary interpretation. Smaller files of processed data and derivative maps, charts, etc., will then be returned to the Mars base for incorporation into on-site interpretations.

Protocols will have been established for communicating exploration news to the public. During the regular briefings, Mars- and Earth-based investigators will select and prepare results and images for public presentation. Public affairs personnel will disseminate the information.

4. TELEOPERATED AND ROBOTIC DATA ACQUISITION AND TRANSMISSION

Employing robotic and teleoperated devices, where appropriate, in support of human exploration of Mars will free the eyes and minds of the explorers for observation, analysis, and synthesis. Teleoperated robots may be utilized on Mars for video surveys of sites, soil sample retrieval, and similar tasks directed from Mars base, much as their counterparts are used in support of deep-sea divers on Earth. NASA currently has flight opportunities scheduled for testing teleoperated instruments in 2001 and 2003.

Examples of Mars surface instruments that might be operated remotely from Earth are the Mössbauer and thermal emission spectrometers. The data derived from these observations could be transmitted directly to Earth, while the crew in the Mars laboratory conducts other analyses. (Physical locations of instruments and contamination issues are discussed elsewhere in this report.) Schedules for teleoperated and Mars-based analyses will be established during regular briefings.

5. COMMUNICATIONS BETWEEN OUT-BOUND AND IN-BOUND CREWS

In the waning days of a mission, explorers on Mars will synthesize their observations and interpretations in collaboration with the scientific team on Earth. By the time of their return, a draft mission report will have been prepared. During the long flights to Mars and back, the homeward-bound crew will brief incoming astronauts on both the state of scientific research and on the practicalities of living and working on the planet. In addition to activities such as the planned long-baseline astronomical studies, some transit time may also be dedicated to exercises and experiments designed to hone the analytical skills of the Mars-bound crew.

6. CONCLUSIONS

The Apollo program taught us vital lessons about communicating with explorers on another celestial body. Long-duration Skylab and Mir missions reinforced those lessons: Over-communication and micro-management of crew time both seriously impede research. Upon her return from six months on Mir, Shannon Lucid published her reflections on conducting scientific research in space during a protracted mission (*Scientific American,* May 1998). She exhorted schedulers to allow time for contemplation, for integration of ideas — the activities for which human explorers of space are so uniquely equipped.

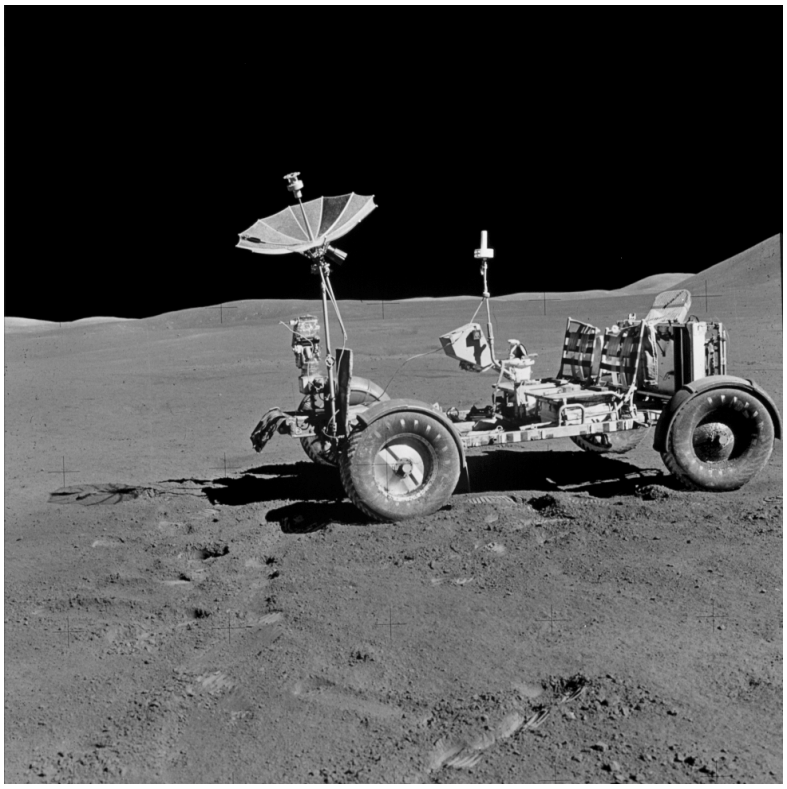


Fig. 14. Communications satellite mounted on lunar rover, returning signal to Earth, Apollo 15.

TEAM IV: RECOMMENDATIONS

1. Mission must provide a communications infrastructure that may include:

- **Satellites**
- **"Black Box" for recording exploration activities**
- **Capability for data compression/transmission**

2. More structured communication early in mission during reconnaissance stage, less structured communication with Earth in later stages

3. Upon landing, landing and descent observations should be maximized in order to:

- **Provide a precise landing location to mission control for navigation and communication purposes**
- **Document landing and any anomalies**
- **Aid in traverse planning early in the mission**

4. Briefing and debriefing should occur between arriving and departing crews

- **When possible considering relative location of space vehicles in transit**

5. Need different "levels" of communication among the scientists

- **Need "backroom"**
- **Engage student/intern level "gophers" (e.g., for immediate needs, like library/Internet searches)**

6. Need capability to communicate with robotic instruments and rovers

- **Earth-run analyses, control direct from earth to instrument (e.g., Mössbauer, APX)**
- **Teleoperations from Mars base or Earth**

REFERENCES

Allen C., Jakes P., Jaumann R., Marshall J., Moses S., Ryder G., Saunders S., and Singer R. (1995) Field geology/processes. In *Planetary Surface Instruments Workshop,* pp. 105–110. LPI Technical Report 95-05, Lunar and Planetary Institute, Houston.

Brack A. et al. (1998) *ESA Exobiology Science Team Study on the Search for Life on Mars.* European Space Agency, ESTEC, Nordwijk, Holland. 107 pp.

Budden N. A. and Duke M. B., eds. (1998) *HEDS-UP Mars Exploration Forum.* LPI Contribution Number 955, Lunar and Planetary Institute, Houston. 241 pp.

Budden N. A. (1994) *Catalog of Lunar and Mars Science Payloads.* NASA Reference Publication 1345. 243 pp.

Duke M. B. (1997) *Mars Surface Mission Workshop.* LPI Contribution Number 934, Lunar and Planetary Institute, Houston. 11 pp.

ESA Final Report (1998) *Exobiology Science Team Study on "The Search for Life on Mars."* June 1998. 108 pp.

Gibson E. K., McKay D. S., Thomas-Keprta K., and Romanek C. S. (1997) The case for relic life on Mars. *Scientific American, 277(6),* 58–65.

Hoffman S. J. and Kaplan D., eds. (1997) *The Reference Mission of the NASA Mars Exploration Study Team.* NASA Special Publication 6107.

Hoffman S. J. (1998) *The Mars Surface Reference Mission: A Response to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Team.* EX13-98-065.

Meyer C., Treiman A. H., and Kostiuk T., eds. (1995) *Planetary Surface Instruments Workshop.* LPI Technical Report 95-05, Lunar and Planetary Institute, Houston.

Portee D. S. F. (1998) Walk this way. *Air and Space, 13(4),* 44–47.

Reilly J. F., Muehlberger W. R., Dickerson P. W., Schmitt H. H., and Young J. W. (1998) Looking back at Earth. *Geotimes,* November, 14–20.

APPENDIX 1: MARS SURFACE REFERENCE MISSION, STEPHEN HOFFMAN, 1998: EXCERPTS

Exploration Field Work

A key objective of the Mars surface mission is to get members of the crew into the field where they can interact as directly as possible with the planet they have come to explore. This section will discuss one of the means by which this will be accomplished – the use of EVAs to carry out field work in the vicinity of the outpost.

Although the list of these field exploration activities will undoubtedly grow as specific objectives are chosen and the means to accomplish them are defined, there are two examples that can serve to illustrate the range of these activities: field geology/mapping and intensive field work at a specific site. Some of the key characteristics of each of these activities, as they apply to EVA, will be described in the following paragraphs.

The activities of a field geologist on the surface of Mars will differ greatly from EVA activities of the Space Shuttle and International Space Station eras. These differences will impact both the design and use of EVA systems for surface activities. Some of these activities and the impacts that will result include the following (*Eppler*, 1997):

> "Geologic field work involves collecting data about the spatial distribution of rock units and structures in order to develop an understanding of the geologic history and distribution of rock units in a particular region."
>
> "It is an oft-stated but correct maxim that the best field mappers are the ones who have seen the most rocks. Geologic field work on the planets, if it is to be worth the significant cost needed to get the geologists there, will require both EVA suits that will allow EVA crew to walk comfortably for hours at a time, and rovers that will allow the crew to see as much terrain as possible."
>
> "One distinction that needs to be emphasized is the difference between field mapping and pure sampling. A popular misconception is that geologists conduct field work purely for the purposes of sampling rock units. Sampling is an important part of field mapping, but sampling in the absence of the spatial information that field mapping provides leads to, at best, a limited understanding of the geology of a particular area. Having said that, the nature of the rock exposure in a given area can limit the amount of field mapping that can be done, and can drive field work efforts to conducting a sampling program that, with some ingenuity, can provide the basics for understanding the broad geologic context of a particular locality."

With this background, a typical field exploration campaign will begin with one or more questions regarding the geology in a particular region and the identification of specific surface features, based on maps and overhead photos, that offer the potential for answering these questions. Traverses are planned to visit these sites, typically grouping these sites together (into multiple traverses if necessary) to meet the limitation of the equipment or environment (e.g., EVA suit duration limits, rover unrefueled range, crew constraints, local sunset, etc.). Depending on the anticipated difficulty of the planned traverse, the crew may choose to send a teleoperated robot to scout the route, sending back imagery or other data for the crew to consider. (Note: these robot scouts are probably surface rovers, specifically the teleoperated rovers mentioned elsewhere in this document, but small aerial vehicles should not be discounted as options for this activity.) In addition, crew safety concerns when entering a region highly dissimilar from any explored before or an area with a high potential for biological activity may dictate the use of a rover in advance of the crew; this contingency is discussed in a later section. The EVA crew walks, or rides if rovers are planned for the traverse, towards the first of these planned sites using visible landmarks and cues available through

the surface navigation system. The crew stops at this site to make observations, record data (e.g., verbal notes to be transcribed later, imagery, sensor readings from those instruments brought on the traverse, etc.), and gather samples as appropriate. If a return visit to this site, either by an EVA team or a robotic device, is deemed necessary to gather additional data or samples, then the position is marked with a small flag or other visible marker or as a "waypoint" for future use within the navigation system used for surface traverses. The crew then proceeds to the next site in the plan until all sites have been visited or until they are required to return to the outpost. At any point in the traverse it may be desirable to stop at unplanned locations due to interesting features that may not have been recognized as such during the planning for the traverse. Similar activities will be carried out by the crew at these unplanned sites. Real time voice and data, along with some amount of video, are sent back to the outpost to those members of the crew that are monitoring the progress of the traverse (along with other duties). On returning to the outpost, the EVA crew will insure that all curation procedures are carried out and that information gathered in the field is transcribed or otherwise stored in the outpost data system. (Sample curation and sample analysis are described in later sections.)

Fig. 2.3-1. An EVA crew member examines a rock sample gathered from the base of a vertical wall. Unpressurized rovers, such as the one seen in the background, will be used by the crew to gain access to site such as these that will likely be located beyond walking distance from the landing site.

Intensive field work at a single site may involve one of several activities associated with science payloads carried in the DRM manifest or comparable activities which may be part of the unspecified "discretionary PI" science. Two specific examples for which there are manifested payloads include the set-up of geophysical/meteorological stations and the 10-meter drill.

Expanding on the case of the 10-meter drill to illustrate this type of activity, there will be several key scientific and operational questions requiring subsurface samples acquired by this tool. Examples include searching for subsurface water or ice, obtaining a stratigraphic record of sediments or layered rocks, or obtaining samples to be used for a search for evidence of past or extant (possibly endolithic) life. A traverse of the type discussed above will probably have been carried out to examine candidate sites for the drill, with the acceptable sites being placed in a priority order. Drill equipment will be moved to the site, most likely on a trailer pulled by either the unpressurized or robotic rovers, and set up for operations. The set up process will likely be automated but with the potential for intervention by the crew. Drilling operations are also likely to be automated

but under close supervision by the crew. (At present, drilling is still something of an art, requiring an understanding of both the nature of the material being drilled through (or at least a best guess of the nature of that material) and of the equipment being used. While drilling is a candidate for a high level of automation, it is likely that human supervision for purposes of "fine tuning" the operations and intervening to stop drilling, will remain a hallmark of this activity.) Core samples will be retrieved by the crew and put through an appropriate curation process before eventual analysis. After concluding drilling at a particular site, the drill equipment will be disassembled and moved to the next site, where this procedure will be repeated.

Because of the nature of the drilling process, there is a high probability that the above-surface equipment will fail or the below-surface equipment will break or seize. Crew intervention is highly likely in either event. In the first case, the crew must decide if the failure can be fixed in the field or if the equipment must be returned to the outpost for repair. Either option will involve some amount of equipment disassembly. If the subsurface equipment fails, the crew must decide how much of this equipment can be retrieved with the tools they have available and whether it is worth the effort and resources to make this retrieval. Due to cargo mass constraints, the drill will not have an unlimited supply of drill bits, auger bits, or drill stem. This makes it worthwhile to expend some effort to retrieve as much of the salvageable subsurface equipment as possible and attempt a repair — the alternative being to halt drilling operations until adequate replacements arrive, probably with the cargo flights supporting the next crew.

The two key characteristics that should be noted here are that drilling activities, and by inference other intensive field work, will involve repeated trips to a single location (or the use of a remote field camp; see the section devoted to this topic) and an extensive interaction with tools and equipment at these sites.

EVA Design and Operational Guidelines

As a practical matter, the examples described above, and other EVA tasks that are identified as the surface mission matures, will be translated into more specific design assumptions and operational guidelines. These will in turn lead to specific requirements and flight rules. Based on past experience, plans for ISS, and current knowledge of the Mars surface mission, this transformation process has already begun (*Griffith*, 1998). While these discussions are on-going and will be subject to change as systems and operations mature, the following list indicates some of the assumptions being proposed for Mars EVA activities.

- The buddy system of paired EVA crew members will always be used.
- Standard EVA protocols such as gloved hand access, no sharp edges, touch temperatures within supported limits, and simplified tool interfaces must be applied to every element expected to be handled or encountered by suited crews.
- A safe haven must be readily available at all ranges beyond walkback distance. (See *NASA*, 1998, for additional discussion of safe haven requirements.)
- Seasonal effects, such as number of daylight hours, dust storms, and possibly radiation events, will be taken into account during planning, timing, and support of EVAs.
- Planned EVA contingency support will account for sickness, injury, and potential incapacitation of an EVA crew member in addition to suit/equipment problems.
- Time delays between Earth and Mars require that primary support for the EVA crew be provided by the habitat crew. Earth-based personnel may participate, but as backup. In both cases, real-time voice, video, and data between the EVA crew and the habitat support personnel are required. Loss of these links may, depending on distance, terminate the current EVA.
- Nominally only one pair of crew outside the habitat or a pressurized rover at a time. It may be possible to have two pair outside in extreme cases, but only for local maintenance/support or one pair rescuing the other.

- EVA during nighttime will be trained and possible, but not nominally planned, and will be constrained to local area (i.e., in the vicinity of the habitat or a pressurized rover).
- The EVA suits will have minimal prebreathe and require minimal turnaround maintenance between uses.

Summary

To summarize, examples described in this section point out several guidelines for surface operations and for development of surface EVA suits and the equipment used by the crews while in these suits:

- "[F]irst is [the] ability for suited crew members to observe the environment around them. First and foremost, geologic field work is an exercise in seeing rocks and structures. The accommodations that allow observation must allow as wide a field of view as possible . . . Further, the visibility provided must be as free of optical distortion [as possible] and preferably without degradation of color vision. In particular, seeing colors allows discrimination between otherwise similar rock units" (*Eppler,* 1997).

- "The second major implication is that EVA suits and other exploration accommodations must allow as much mobility as possible, both in terms of suit mobility and the ability to see as much countryside as possible . . . Where suit mobility is difficult or disallowed by the mechanics of inflated suits (e.g., bending and squatting down), an easily used suite of tools should compensate for the lack of mobility, so rock samples and dropped tools can be picked up with as little effort as possible" (*Eppler,* 1997).

- Tools and equipment must be maintainable in the field and the EVA suit-tool interface must accommodate the environmental conditions under which this maintenance will take place. The level of maintenance that must be accomplished in the field vs. maintenance at the outpost has yet to be determined. However, guidelines on maintenance activities are discussed in a later section of this document.

- Communication between the EVA team in the field and the outpost as well as navigational aid for the EVA team while in the field are two capabilities that apply to all the field activities envisioned for the surface crew.

References

Eppler D. (1997) *Geological Field Work and General Implications for Planetary EVA Suit Design.* Internal Memo, February 7, NASA Johnson Space Center, Houston, Texas.

Griffith A. (1998) Personal communication.

NASA (1998) *Human-Rating Requirements.* JSC Publ. No. 28354, NASA Johnson Space Center, Houston, Texas.

Surface Transportation

Surface transportation for EVA crews will be a requirement from the outset of these Mars missions. There are several factors contributing to this. First, safety considerations for landing may drive landing site selection to a location that is free of terrain features that have the dual distinction of being both "landing hazards" and "interesting geological sites." Second, a crew will exhaust interesting sites within walking distance during an 18 month surface mission, even if there are only a modest number of EVAs allocated for the mission. Third, regardless of how well mission planners can "centrally locate" the landing site, there will undoubtedly be important sites either located at a significant distance from the outpost or at which extended times

are necessary to fully explore the area. Thus the capability to travel easily and quickly away from the landing site will be necessary for the crew to remain fully productive throughout the surface mission.

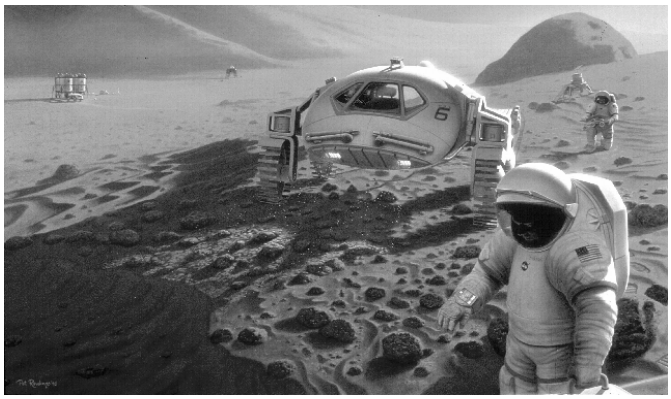


Fig. 2.4-1. EVA crew members begin to explore the region in the immediate vicinity of the landing site. Pressurized rovers, such as the one illustrated here, will be used for a variety of tasks both close to and distant from the pressurized habitat. These rovers will have the capability to allow the crew to conduct EVAs, as required, in the vicinity of the rover.

There are two options for crew surface transportation typically mentioned in Mars mission studies (e.g., *NASA*, 1997): unpressurized (and thus limited duration) rovers, and pressurized (and thus extended duration) rovers. Each has its advantages, which tend to be complementary, and the availability of both types will provide flexibility for surface operations.

Unpressurized Rovers

Unpressurized rovers will obviously require the use of EVA suits by the crew. This implies that the capabilities and interfaces of the unpressurized rover will be intimately tied to those of the EVA suit. This, along with the previously stated reliance on surface transportation for the crew to remain at a high level of effectiveness over a long duration, allows the unpressurized rover to be viewed in may ways as an extension of the EVA suit. From this perspective, many of the heavier or bulky systems that would otherwise be an integral part of the suit can be removed and placed on the rover, or the functionality of certain systems can be split between the suit and the rover. In the case of off-loading capabilities to the rover, navigation, long range communication, tools, and experiment packages can be integrated with or carried by the rover. In the case of splitting functionality, any of the various life support system consumables (e.g., power, breathing gases, thermal control, etc.) can be located on both the rover and within the EVA suit. This division or reallocation of EVA support functionality may restrict the maximum duration of the EVA suit to something less than that which has been previously demonstrated. However, analysis of Apollo EVA activities using the Lunar Rover Vehicle (LRV) indicate that approximately 20 percent of the total EVA time was spent by the crew on the LRV moving from site to site (Trevino, 1998). Mars surface operations can be assumed to be comparable. Thus the EVA team will have sufficient time for recharge of EVA suit consumables or switching to rover-based support systems to preserve EVA suit consumables. Providing multiple sources of consumables and support systems in the field also enhances crew safety by providing contingency options should EVA suit systems degrade or fail.

Operationally, Mars surface EVAs will be conducted by a minimum of two people and by a maximum of four. (This will always provide for a buddy system while on an EVA but will also leave at least two people in the surface habitat for contingency operations should they be needed.) If unpressurized rovers are used, then an additional operational constraint will be imposed on the EVA team. If one rover is used, then the EVA team will be constrained to operate within rescue range of the outpost. This could mean either the team has sufficient time to walk back to the outpost if the rover fails, or there is sufficient time for a rescue team from the outpost to reach them. Taking multiple, and identical, rovers into the field allows the EVA team to expand its range of operation because these vehicles are now mutually supporting and thus able to handle a wider range of contingency situations. It is reasonable to assume that, while operating in terrain similar to that seem in images of the

martian surface, a rover could easily become stuck or otherwise unable to move but is still functional. In a single rover operation, this would be sufficient cause for the EVA team to start walking back to the outpost or to call for assistance from the personnel remaining at the outpost. However, under these circumstances rovers not immobilized are available to help extract the temporarily immobile vehicle. In the case of a disabling component failure, the other rover(s) are available to provide power, lighting, etc., as field repairs are attempted or, in a worst case, transport the crew of the failed rover back to the outpost.

Fig. 2.4-2. Interior view of a pressurized rover as the crew prepares for an EVA at a site located some significant distance from the pressurized habitat.

This description points out two additional characteristics of the unpressurized rovers. First it points out that these rovers must be reliable but also easily repairable in the field (or at least have the capability to be partially disassembled in the field so the failed component can be returned to the outpost for repair). Second it indicates that the rovers must be sized to carry cargo which, if off-loaded, is of a sufficient capacity to carry the crew of a disabled rover.

Within these constraints, the unpressurized rovers will be capable of supporting any of the various EVA activities discussed in previous sections.

Pressurized Rovers

Pressurized rovers are typically included in the Mars mission studies because of their ability to extend the range of the crew, in terms of both distance and duration. While exact distances and durations will be dependent on the specific site chosen, the intent of a recent NASA Mars mission study (*NASA*, 1997) was to reach locations several hundred kilometers from the outpost for durations measured in days to weeks between resupply. It was also the intent for the crew using the pressurized rover to be capable of performing many of the same functions as at the outpost, but at a reduced scale. Thus a crew using a pressurized rover can be expected to be capable of commanding and controlling teleoperated rovers, conduct EVA activities (comparable to those discussed earlier) within the vicinity of the rover, and otherwise support the crew for the duration of their excursion away from the outpost.

Due to the size and mass of a pressurized rover, only one of these vehicles is manifested in any one cargo flight. Based on the mission architecture described in section 1.2 of the addendum to the Mars Reference Mission document (see *NASA*, 1998) the first pressurized rover will arrive on the cargo flight for the second crew. Due to the sequential deployment of these cargo vehicles, this pressurized rover will arrive in time for the first crew to use it (see Fig. 1.2-2). But the availability of only one of

these pressurized rovers will impose operational constraints on its use until a second rover arrives.

During that period of time when only a single pressurized rover is available, operations will be constrained in a manner similar to that imposed on multiple unpressurized rovers: namely the pressurized rover must remain within range of the unpressurized rovers to allow for rescue should the pressurized rover become immobilized or disabled. While this circumstance does not allow for the rover to be deployed at great radial distances from the outpost, it does offer some interesting uses that can be equally productive. In one example, the pressurized rover can be used as a temporary base camp at a location where intensive field work will be carried out for an extended period of time (e.g., the drill) but still within unpressurized rover "commuting" distance of the outpost (see the following section on field camps). Crews can be exchanged and consumables can be resupplied for as long as the field work continues at that site. In a second example, the pressurized rover can be used to "circumnavigate" the outpost site at a distance defined by the range of the unpressurized rover rescue constraint. This will allow a traverse of potentially hundreds of kilometers to be conducted, visiting a significant number of sites along the way. As with the fixed site scenario, crews and supplies can be delivered periodically to the pressurized rover as it makes its way around the outpost site.

Once a second pressurized rover has been delivered, in time to support the second crew as currently planned, the radial distance away from the outpost can be significantly expanded. These distances will preclude resupply as mentioned previously and thus the maximum range will be limited by the consumables brought along with the pressurized rovers. The following scenario illustrates a potential long-range deployment of two pressurized rovers.

> An interesting site with potential lacustrine deposits, and thus a potential site for evidence of past biological activity, has been identified at a range beyond that which can be supported by unpressurized rovers. A teleoperated rover is sent to the site to test for toxic or biological hazards (see the following section devoted to this topic) and returns with a small sample for analysis at the outpost. After determining that no immediate hazard is posed to the crew, a four person team is deployed to the site in the two pressurized rovers. These rovers are towing the 10-meter drill, a teleoperated rover, and at least one unpressurized rover. On arrival at the site, the teleoperated rover and a two person EVA team, using the unpressurized rover(s), perform a more detailed reconnaissance of the area and specifically examine candidate sites for the drill. The candidate sites are prioritized by the entire crew, collaborating with colleagues on Earth. The pressurized rovers are moved to a central location among these sites where they will remain as a base camp, primarily to conserve as many of the pressurized rover consumable resources as possible. The drill is moved to each candidate site in turn by an EVA crew using the unpressurized rover. The EVA crews "commute" to each site, using the unpressurized rover, until drilling operations are completed at that site. Core samples from the drill are tested for biological activity or toxic substances using sensors onboard the teleoperated rover prior to contact by the EVA crew. The core samples are then put through an aseptic curation process and stored for return to the outpost where further analysis will be performed if appropriate. After collecting core samples at all of the candidate sites, the crew will use any remaining time (as dictated by their consumables supply) to continue a reconnaissance of the area or to return to the outpost by a different route, visiting other sites of interest along the way.

As discussed for the unpressurized rovers, dual pressurized rover operations allow for mutual support in the field. It also implies that limited maintenance and repair in the field should be possible, with the contingency capability for a single pressurized rover to bring the entire deployed crew should one of the pressurized rovers be disabled beyond the capability for the crew to repair it in the field.

Summary

This section has discussed the types of surface transportation that will be available to the crew and the variety of missions on which they can be deployed. Important points include:

- Both pressurized and unpressurized rovers will be available to the crew.
- The two types of rovers complement one another in the field activities that can be accomplished.
- Crew safety and the number of rovers deployed will determine the maximum range and duration that can be attained.
- Field maintenance will be a necessity.
- The unpressurized rover can be viewed as an extension of the EVA suit; allocation of functionality between the two systems needs further research.
- Dual pressurized rovers will allow distant sites to be visited or extended operations to be accomplished at selected sites.

References

NASA (1997) *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team.* NASA Special Publication 6107, NASA Johnson Space Center, Houston, Texas.

NASA (1998) *Reference Mission Version 3.0; Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Team.* EX13-98-036, NASA Johnson Space Center, Houston, Texas.

Trevino R. (1998) Personal communication.

The Field Camp

A primary objective of sending human crews to Mars is to allow them to explore, in person, a region containing diverse, interesting surface features. However, operational and safety requirements will impose constraints on those locations where the crew and their cargo vehicles will be allowed to land before they can begin these explorations. Planetary protection protocols may also limit landings to those regions from which samples have been returned to Earth by a robotic spacecraft — samples that have proven sterile and biologically safe. Additionally, landing sites may be restricted to those areas that are relatively benign in terms of hazards and trafficability. These requirements of diversity and safety may well work against each other, perhaps placing the interesting sites only within reasonable proximity to the safe/benign landing sites. It is to be expected, given the diversity of martian geology, that one or more of the key sites identified for exploration by the crew will be located some significant distance away from the landing site.

It is also reasonable to assume that some of these remote sites will be selected for extended, detailed study by the crews. Activities such as deep drilling, trenching and other forms of surface excavation, or simply detailed study of certain features (e.g., sedimentary layering found in ancient lake beds or that are exposed at a cliff face) will require periods of time greater than are reasonable for a single EVA.

The capability to remain at one or more of these remote sites for extended periods of time — through the creation of a field camp — will greatly enhance the productivity of human exploration. Such a capability will reduce the need for the crew to commute from the central base to the site and back again, thereby providing the means for exploring a site for periods of time longer than are possible in a single EVA.

In addition to the previously mentioned drilling and digging activities, this capability will allow walking or unpressurized rover traverses to extend beyond what is possible from the central base prior to the arrival of multiple pressurized rovers. In this case, the field camp could be located at the maximum range allowed by operational considerations (e.g., the unsupported walkback distance allowed by EVA suit consumables or crew fatigue limits) and would then serve as the staging base from which additional traverses would be carried out (see Fig. 2.5-1). Communication systems at the field camp will serve as a data relay between parties in the field and the remainder of the crew at the central base.

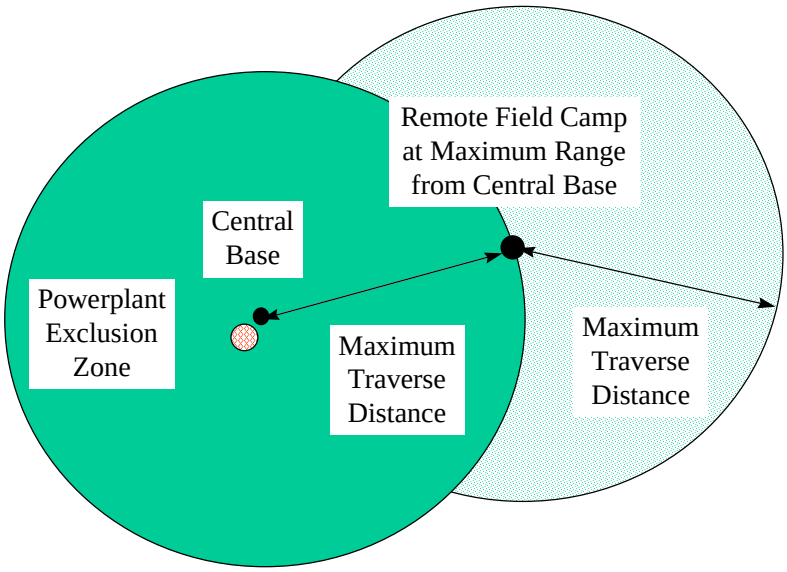


Fig. 2.5-1. Use of a remote field camp to extend the range of operation prior to the arrival of long-range roving capability.

A secondary use for this field camp capability is to provide an emergency camp to which a crew could walk in case of a rover breakdown beyond walkback distance to the central base. It would also be the agreed-to point from which a search and rescue group would start its search in case contact is lost with a team in the field (the assumption being that if a crew should lose radio contact but is otherwise okay, then this crew will make its way back to the field camp to meet the SAR crew from the central base).

Typically, site(s) for a field camp will be chosen to meet certain mission objectives; there may be several field camps established during the course of the 18-month surface mission. Each site will be selected based on remote sensing data gathered from orbit or by teleoperated robots (either airborne or moving across the surface) or may have been identified by the crew during the course of a previous surface traverse. Supported by their terrestrial colleagues, the crew will plan the content and timeline of likely activities to be spent at this site, allowing necessary equipment and supplies to be identified. Unpressurized rovers (and, when available, the pressurized rovers) will be used to transport equipment and supplies to the site. More than one trip by rover to the site may be required. Sample payloads that could be transported to this remote site are listed in Table 2.5-1 (these values are taken from Tables 3-5, 3-7, and 3-9 from *NASA*, 1997).

TABLE 2.5-1. Sample payloads and associated mass values that may be used at remote field camps (mass estimate derived from *Budden,* 1994).

Payload Description	Payload Mass (kg)
Field Geology Package: geologic hand tools, cameras, sample containers, documentation tools	335
Traverse Geophysics Instruments	400
Geophysics/Meteorology Instruments (8 sets)	200
10-meter drill	260
1-kilometer Drill	20,000

Other field camp infrastructure, such as a pressurized habitation structure, power system, and life support consumables, must also be transported to the field camp site. The mass of these items is implementation dependent and has not yet been specified. However, two possible implementations are readily envisioned and will be noted here to illustrate the range of options.

The first possible implementation is to use on of the pressurized rovers as the habitat and power system for the field camp. This rover will have already been designed to support several crew for many days away from the central base and thus will meet these needs for the field camp. The pressurized rover can tow at least a portion of the other equipment to the site and then be parked in a convenient location near the other activities taking place. Crew mobility while the pressurized rover is in this fixed location can be accomplished by the unpressurized rovers.

The second implementation is to use a smaller version of the inflatable habitat already in place at the central base. Such a system could be towed into position and set up by the crew. The technology used for the inflatable pressure vessel as well as other rigid structure (such as the airlock door) would be the same as that used at the central base. Other systems, such as power and life support, could be variations on the technology used for the pressurized rover or that used at the central base.

The first activity for the crew at the field camp will be to choose specific sites for the major elements of the camp, such as the habitat, associated support equipment, and major scientific experiments. Equipment to be used at the site is assumed to be designed such that minimal site preparation (i.e., moving rocks, surface leveling, etc.) will be required, with one exception. If a radiation storm shelter capability is not included in the equipment brought to the site, construction of such a facility may be required. The same equipment used for the trenching activity discussed elsewhere in this section can be used to excavate a suitable subsurface location that could be covered with regolith. The crew will then set up and verify the readiness of the habitat, life support system, power system, communication system. Only after these elements are operational will the crew begin to set up and operate the science equipment.

The primary purpose for a field camp capability is to place the crew in close proximity to features or items of scientific interest. Thus the capability for daily EVA activities is assumed for these field camps. As mentioned in various other places in this section, EVA activities may be as uncomplicated as walking traverses in the vicinity of the field camp to the set up, operation, and maintenance of substantial equipment, such as drills or trenching tools. The capability for delicate excavation, such as might be used at an archeological dig, will also be necessary for those activities designed to carefully “peel back” layered deposits.

Fig. 2.5-2. Crew operating from a field camp will allow interesting sites to be explored in more detail than would be possible if the EVA were staged from the landing site.

Because of the emphasis on external activities while at the field camp, activities internal to the habitat will tend to be focused on supporting these activities. Basic capabilities for meal preparation, personal hygiene, and sleeping accommodations will be provided. Other activities likely to be carried out by the field camp crew will focus on preparation for the next EVA. This includes any required maintenance or minor repair of the EVA suits, logging data from the experiments, and preparing samples (such as core sample from the drill) for transportation back to the central base. Major repair of equipment, if needed, is assumed to be accomplished at the central base.

Because this field camp will be within a reasonable distance of the central base (possibly no more than walkback distance) it affords the option of resupplying the camp with materiel from the central base. This capability can allow systems to be sized for a smaller capacity than might otherwise be required and opens the possibility for using open loop systems (e.g., power or life support) supplied by the cache of life support and propellants being produced by the ISRU plant. It also opens the option for changing crews at the field camp so that no one group is away from the amenities of the central base for an extended period of time. The amount of supplies on-hand should exceed the resupply frequency by several days to allow for contingencies. A nominal resupply frequency of one week is suggested to coincide with other cyclic events observed by the crew. In addition, a field camp is assumed to be capable of supporting a nominal crew of three people between resupply events.

Once activities at the field camp have been completed, the crew will dismantle equipment and structures for return to the central base or relocation at a different site. An alternative use for some of the field camp equipment is to leave it in place to serve as an emergency camp and supply cache. At a minimum, the radiation storm shelter (if constructed in place) will remain at the site and could be used as a storage location for emergency supplies. The crew will return all data and samples gathered at the field camp to the central base where the data will be archived and samples will either be analyzed with the equipment available or will be put through the curation process.

Summary

To summarize, this section has discussed the key mission objectives satisfied by and functional capabilities of a remote field camp. These include:

- Improved utilization of crew by providing the capability to remain in the field for many days or weeks (with resupply) at sites of high scientific interest.
- The ability to perform daily EVAs.
- The ability to support a diversity of experiments ranging from walking traverses to operation large and/or complex machinery.

- The ability to accommodate a nominal crew of three.
- The ability to resupply consumables from the central base on a periodic basis, nominally once per week.
- The ability to relocate the field camp once activities at a given site are complete.

System definition and trade studies remain to be performed on the habitation and supporting systems that are needed to implement this capability.

References

Budden N. A. (1994) *Catalog of Lunar and Mars Science Payloads.* NASA Reference Publication 1345, NASA Johnson Space Center, Houston, Texas.

NASA (1997) *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team.* NASA Special Publication 6107, NASA Johnson Space Center, Houston, Texas.

Toxin and Biohazard Assessment

Two highly interrelated and possibly conflicting aspects of human missions to Mars are the maintenance of a healthy crew while at the same time actively seeking out evidence of extinct or extant martian life. The means by which both of these aspects of a Mars mission are satisfied will be a combination of equipment and procedures designed to alert the crew to potentially toxic materials or to the presence of biological activity while keeping the crew safely isolated should either be encountered.

Toxicity at some level is a likely property of the martian dust. Viking analyses demonstrated two pertinent characteristics of martian surface material that leads to this conclusion. First, the dust contains an active oxidant at levels of 100 parts per million and, second, no carbon compound could be found in the dust. This has been interpreted to mean that the surface of Mars is sterile and that oxidation processes have destroyed any carbon that may have been brought to the surface from the interior or from outside by meteoroids. For comparison, the lunar regolith contains detectable carbon from carbonaceous chondrite (asteroid) sources. Chemical and physical effects of oxidants in the martian soil on humans could range from none, to annoying, to potentially dangerous if steps are not taken to remove or modify the contaminants. The dust is very fine-grained, with windblown dust sizes typically in the 1–2-µm range, based on settling properties in the martian atmosphere. This material is exposed to an ultraviolet radiation environment, which could activate mineral grain surfaces. The mineralogy of the dust is unknown. However, it is likely that some of it is highly soluble in water and could react with the respiratory system of astronauts if not somehow removed. This dust could also, in principle, include metallic chlorides or nitrates with noxious properties. It will be difficult to prevent the contamination of the interior of the martian habitat with at least some amount of surface dust if EVAs are a major activity, as they are proposed to be in the exploration strategy.

Most scientists also believe that the Viking data showed that the surface does not contain living organisms and thus is not expected to impede the first robotic sample return missions. However, initial biological studies with these returned samples will be aimed at verifying the results of the Viking analyses. If the current interpretations are incorrect and there are viable martian organisms in the martian soil, then additional precautions will be needed for the human missions. If the organisms are found not to be harmful, or are shown to be not viable in the Earth's atmosphere, then they should pose no problem to future human missions. If the organisms are found to be harmful to humans or dangerous if released into the terrestrial biosphere, then the level of danger will have to be assessed and additional precautions taken for human missions, to avoid exposing unprotected astronauts to the organisms and introducing untreated dust to the Earth's biosphere. In an extreme case, it might be prudent to not send humans to Mars.

If, as expected, the surface of Mars is sterile, the concern for biological activity in Mars will remain. This is because one of the objectives of human missions is likely to be the search for life in isolated environments, particularly below permafrost at depth and in areas of hydrothermal activity. In these cases, samples will be needed from below the surface and new, unoxidized environments will be encountered. These new environments will have to be treated as if they contained harmful organisms until proven otherwise. The crew will have to be protected from encountering primary contamination by direct exposure to the samples. They will also have to avoid coming in contact with anything that has contacted those samples (drilling tools, containers, etc.).

The potential for discovering martian life also requires that the environments in which life may exist be protected from contamination or disruption. For scientific purposes, these environments must remain uncontaminated by terrestrial organisms that could confound results, change the environment, or otherwise disrupt or destroy the indigenous organisms. (It is also held by some that ethical considerations will require that no contaminants be introduced until it is known that the environment does not contain viable martian organisms.) This will require that any procedures used to obtain samples in these environments be treated with at least the same level of control now required for life detection experiments on robotic missions. Because humans will be in the vicinity, however, protection procedures will be more complicated and they will have to be performed on Mars. Learning about the fate of terrestrial organic contaminants in the martian surface environment is also an important aspect of the design of such systems. If, for example, the surface environment is self-sterilizing on a rapid time scale, contamination protection will be less difficult than if organic constituents survive for significant time periods in the surface environment. It is likely that terrestrial microorganisms will either die or be unable to reproduce in the cold, dry, oxidizing, high UV radiation environment of Mars' surface. If, however, terrestrial microorganisms do not die, become inactivated, or react quickly when exposed to the surface environment, the potential exists for dust storms to distribute them widely over the planet.

Initial assessments for toxicity and biohazards will be part of the robotic missions that precede humans to Mars. Robotic missions will be used to gather data about the soil and dust found on the martian surface and will be used to return small samples to Earth so that these questions, among others, can be addressed. Analyses of surface soil and dust samples will allow the magnitude of the threat, if any, to be determined, and will provide a basis for the mitigation of the toxic or deleterious effects of soil on humans. It will also be possible to define the potential interactions of the dust with mechanical and electronic systems, and to develop procedures for removing or modifying the dust in the habitat interiors.

Once the martian surface has been found to be generally safe for humans to occupy (or satisfactory mitigation processes have been developed), toxicity/biohazard assessment activities will focus on those new or isolated environments where the crews will continue their search for evidence of past or present life. In support of these forays, robotic vehicles will be sent in advance of the crews, carrying appropriate sensors to allow them to function as "mechanical canaries". These robots will search for known toxins or evidence of biological activity and relate their findings to the crews. This implies that a single purpose robot should be kept in isolation to avoid contamination by contact with the crew or that adequate cleaning/sterilizing procedures be developed to avoid false positive signals from these sensors.

A similar warning capability will be needed to perform the same function in bore holes or other subsurface excavations, particularly if these activities penetrate into regions containing liquid water. The alternative is for samples taken under these circumstances to be considered hazardous a priori and to provide the crew with the means for containing and isolating the samples until proper handling can take place. The astronauts may take two approaches with such samples: they may be collected and packaged immediately for return to Earth, or it may be desired to make some analyses on Mars. In either case, continued separation of the crew from the samples is needed. The level of analysis that is reasonable for conduct on the surface of Mars is TBD; however, it is pointed out that a principal reason to have humans on Mars is to conduct analyses as exploration pro-

ceeds, so that discoveries can be folded back into the exploration plan. Thus, it is likely that the full range of analytical capability of the martian laboratory facility will be applied to the samples, in addition to biological activity determinations. This indicates that there will be a need for a sample isolation chamber, perhaps a standalone facility external to the habitat, where samples can be handled, split, packaged, either for return to Earth or transfer into the Mars analytical laboratory. It may be necessary to provide a capability to sterilize samples, as well. (Sample analysis is discussed in a later section.)

If these assessment activities have determined that the new environments do not pose a toxicological or biological hazard to the crew (or conversely, that the crew does not pose a hazard to the environment), then the crew will be allowed to approach the site for detailed exploration. This will also be the criterion that will be used to decide when the crew can safely handle samples within their Mars analytical laboratory.

Despite these various precautions, EVA crew members or equipment may become contaminated during the course of their exploration activities. A final set of sensors will be in place at the entrance to, or within, the airlock to check crews returning from EVA activities. Cleaning/sterilization procedures will be needed for both the EVA suits (or associated equipment brought into the airlock), and for the sensors used to detect possible hazards, to remove the hazardous material prior to allowing the crew members to reentry the habitat facility.

When humans were sent to the Moon, a system of quarantine for the crew and samples on return to the Earth was instituted. For Mars, the analysis of samples returned robotically could provide data and guidance to procedures that would significantly reduce the risk of bringing uncontrolled dangerous materials into the Earth's biosphere (robotic sample returns from the Moon came after the first human missions). However, even with the information from robotic sample return missions, it is likely that samples collected by humans will continue to be quarantined throughout the Mars program and that the crews will be isolated for some period of time on returning to Earth. This will continue as long as new environments are being encountered on the human missions. This suggests that requirements for crew quarantine be considered at the time that sample quarantine facilities are designed for robotic sample return missions. It also suggests that quarantine testing and certification for controlled distribution of samples that are developed for the robotic program will be continued, at least for some samples, during the human program.

Summary

In summary, there will be an ongoing need for crews to evaluate the level of toxicity or potential for biological activity throughout all phases of the surface mission. The active search for evidence of past or present life will inevitable lead these crews to environments where such assessments will be necessary to assure their own health and safety as well as protect to Earth's biosphere from contamination. Such assessments will be derived from equipment and procedures that exhibit the following characteristics and capabilities:

- Control of potential toxic effects of Mars' dust on humans, through separation of humans from the environment, cleaning, and deactivating toxic materials.

- Special precautions to protect crews from samples taken from isolated environments that may harbor martian organisms.

- Capability to make analyses of the characteristics of samples taken from these isolated environments, without exposing the astronauts to potential martian organisms.

- Special aseptic sampling and packaging procedures for samples with possible martian organisms.

- Quarantine procedures for samples and crews, whenever new environments are sampled that may contain martian life.

- Capability to prevent contamination of isolated martian environments that may contain organisms from contamination or disruption by human activities.

Sample Curation

During the course of their 18-month stay on the martian surface, the astronaut crew will conduct many EVAs and teleoperate many robotic rover traverses. A large subset of these EVAs and robotic rover traverses will be focused on collecting geologic samples from a variety of sites around the outpost. The proper handling and curation of these samples is critical to ensure that any specimens chosen for shipment to Earth are minimally contaminated.

Sample curation includes documentation, sample tracking, sample splitting, preliminary examination, contamination control, and storage. This discussion focuses on the handling of rock samples and soil scooped from the surface, and is primarily based on curation concepts developed for a lunar outpost (*Treiman,* 1993). The schemes described below would not be appropriate for core samples (drill or drive tube) or volatile-rich (i.e., icy) samples. These special cases will be discussed at the end of this section.

The curatorial history of a rock or soil sample begins when a crew member, or a robotic explorer, observes something of special interest or finds an object specifically being looked for. Before that sample is actually collected, documentation of its location, orientation, and surface setting will be recorded. This can be done by photographic and/or video equipment and a recorded verbal description of the sample and its surroundings. This documentation step is important in that once a sample is removed from its environment the context of its relationship with the local area will be physically lost, and only good records will allow researchers to recreate the surface setting.

If possible, the sample will then be split in place into two representative subsamples. If pieces are being chipped off exposed bedrock or a large boulder, two similar samples will be taken. This is done so that one subsample can be used for preliminary examination at the outpost habitat, while the other can be put in storage away from the habitat for possible transport to Earth. In this way, at least one minimally contaminated sample will be preserved from every collection site. “Minimally contaminated” refers to samples only exposed to contamination derived from sample collection and storage. The mere act of collecting samples on Mars contaminates them due to the outgassing from an astronaut’s space suit, a robotic rover vehicle, or even EVA tools and containers. This level of contamination is unavoidable, as it was during the Apollo program, but experience with lunar samples suggests it will not impede or prevent detailed analyses on Earth (*Treiman,* 1993).

After splitting, the subsamples will be “bagged and labeled.” The bags used to hold the samples would prevent cross contamination between samples, and will most likely be similar to the those used on the Moon during the Apollo program (*Allton,* 1989). However, the choice of materials needs further study because Teflon, like that of the Apollo bags, abrades and rips easily and can lose much of its strength from long exposure to solar radiation (*Treiman,* 1993). The small sample bags will then be loaded into a larger storage bag or container which can be carried on the astronauts’ space suits, mounted on their roving vehicle, or mounted on a robotic rover.

When an EVA or robotic rover traverse is completed, the collected samples will be delivered to two separate storage areas. One area will be distant from the outpost to avoid contamination from gases emitted from the habitat, local surface activity around the outpost, and exhaust gases resulting from spacecraft launches and landings. The exact distance between this re-

mote storage area and the outpost will generally be on the order of one kilometer to a few kilometers. The subsamples earlier referred to as 'minimally contaminated' will be stored at this area, and will include those specimens ultimately chosen for shipment to Earth. The second storage area will be located at the outpost, where subsamples can be easily retrieved for preliminary examination in the habitat's laboratories (see Sample Analysis Section). These samples will experience varying degrees of contamination during examinations and tests, and will likely remain on Mars near the outpost.

The storage areas can range from simply organizing the collected samples in a grid on the surface (i.e., a "rock garden") to housing the samples in a container, structure or building. While the "storage shed" concept was considered optimal for samples on the Moon (*Taylor and Spudis*, 1990), it is possible that the storage structure on Mars might increase the contamination level of the samples, and might have a considerable cost in terms of mass delivered to Mars. Some sort of deployable shelves open to the martian environment may be a good compromise.

Once placed in a storage area, data such as a field description of the sample (i.e., crystalline, breccia, soil, etc.), a sample identification number (preprinted on sample bags) and physical location where the sample is stored (i.e., bin number), would be entered into a computerized database for tracking purposes. During the span of 18 months many samples will be accumulated, and there is the potential for samples getting "mixed up" or "lost." Sample tracking will become more important as the number of collected samples increases and as preliminary analyses begin. It is quite possible that certain samples may need to be retrieved from storage more than once as a better understanding of the local geologic setting is developed by the results of preliminary examinations. However, after the initial data entries (which could simply be a voice transcription) by the EVA crew or by a crew member teleoperating a robotic rover, all maintenance of the tracking database can be done by personnel on Earth.

As mentioned at the beginning of this section, cores (from either drills or drive tubes) and volatile-rich samples will require special treatment. On Earth, cores are extruded, excavated in several phases and sampled continuously over their whole length; a process requiring a considerable amount of time and equipment (*Treiman*, 1993). This level of handling and processing will quite likely be impossible at a Mars outpost, due to the confined volumes in a habitat and the amount of crew time that will be required. One possible approach to overcome these limitations is to not withdraw continuous coring sections but rather sampling the bottom of the drill hole from time to time with a sampling device. This will require a change in the tool for each sample which may allow for a single-use, sterilized sample acquisition device to be used for these samples. However, this is a substantial problem that warrants more discussion, as subsurface information derived from cores will be significant in understanding the local geology around the outpost and thus for real-time planning of further research and exploration.

Volatile-rich samples will also present significant challenges in keeping them in their pristine state. Samples such as permafrost or clays, if found, would require specialized containers to provide a constant temperature for the preservation of any ices and to control any pressure increases due to out-gassing. How to handle these volatile-rich samples deserves special attention because the discovery of water in any form would be extremely important in the search for signs of past or present life.

Summary

In summary, the following curatorial activities will be conducted during any extended stay by astronaut crews on the martian surface:

- Sample documentation: to record the geologic and physical setting of the sample prior to collection, and to describe everything done to that sample during examinations.
- Splitting of selected samples: to provide subsamples for preliminary examinations and "minimally contaminated" sub-samples for remote storage and possible shipment to Earth.

- Sample storage: to maintain samples in as pristine and secure condition as possible and be readily accessible.
- Sample tracking: database of current information pertaining to the location and condition of all samples and subsamples.
- Preliminary examination: conducted to identify and characterize each sample and subsample.
- Contamination control: to maintain samples in as pristine condition as possible.

References

Allton J. (1989) *Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers.* NASA JSC-23454.

Taylor G. and Spudis P., eds. (1988) *Geoscience and a Lunar Base: A Comprehensive Plan for Lunar Exploration.* NASA Conference Publication 3070.

Treiman A. (1993) *Curation of Geological Materials at a Lunar Outpost.* NASA JSC-26194.

Sample Analysis

A key, distinguishing feature of these Mars missions will be the interaction of field work (as discussed previously) and in situ sample and data analysis. During the Apollo missions to the Moon, all rock and soil samples collected were put directly in sample return containers; no preliminary analyses, other than the astronauts' verbal field notes, were conducted with the samples. In addition, all other photographs and observational field notes were recorded and stored without benefit of any time for reflection or opportunity to revisit any of the sites. This mode of surface geoscience operations was necessary due to the short duration of the surface stays (3 days at the most), the constrained volume of the spacecrafts' habitable volume, and the lack of time on the astronauts' schedule. The Mars surface mission, as currently envisioned, changes this paradigm with a much longer period of time on the surface and a planned capability for conducting some level of sample analysis before returning to Earth. Facilities on this kind of mission will never approach the capability of those in laboratories on Earth, however some level of on-site analytical capability will be needed for the crew to better understand their surroundings and remain adaptive to discoveries made. A key area of investigation as plans are made and technologies are developed for this mission is to decide where to divide the analytical capability that is needed on Mars from that which will be brought to bear on those samples and data returned with the crew.

The extended amount of time on the surface, approximately 18 months, will allow members of the crew to consider what they have seen and collected, in terms of samples and other data, before departing. This additional time will also allow for collaboration with colleagues on Earth to discuss thoughts and theories to explain these data, with the added advantage of opportunities to gather other samples or data from the same location or different locations to support or refute ideas put forth in these discussions.

Sample analysis will also support a number of other surface mission objectives. Key among the objectives of these preliminary examinations will be:

- to develop an understanding of the local geology and geologic history
- to assist in the planning of surface exploration activities and field work
- to "high-grade" the collected samples to determine which ones will be shipped to Earth
- to look for any physical or chemical signs of life, past or present.

Previous sections have described the collection of samples, which will take the form of rocks, soils, and cores. The cores could be taken from a drill or drive tube and may be either dry or volatile rich (i.e., containing ices or liquids or gases that are soon lost if not contained or sampled).

The function of preliminary sample examination presents a great variety of options for where it occurs, how it occurs, and who conducts the examination. Initial sample examination will occur in the field, carried out by either an EVA crew member or a teleoperated robot or possibly both, depending on how the sample analysis equipment is distributed between the EVA crew member and the robot. Once the necessary curatorial tasks have been completed, including the packaging of a minimally contaminated sample, the crew member or robot may examine the rock or soil sample with a hand lens (or its equivalent) or with relatively simple analytical equipment that has been brought into the field. The crew member (either in the field or at the robot's teleoperation station) will use this quick initial assessment to decide if more time should be spent in this area or to place some priority on the order and degree to which this sample is examined at the habitat. For preliminary examinations on the Moon, the geoscience community has recommended that examinations be performed outside of a habitat, and far from the habitat to reduce sample contamination to a minimum (*Taylor and Spudis,* 1990). However, by introducing a sample splitting scheme to provide for minimally contaminated sub-samples (as discussed in the Sample Curation Section), others have advocated examinations inside the habitat (*Treiman,* 1993). For the reasons discussed by *Treiman* (1993), detailed examination of the samples within the habitat (with suitable protection for the crew and for the sample) is currently assumed for the Mars surface mission.

Prior to a more detailed examination inside the habitat, the sample(s) may require some amount of preparation exterior to the habitat. An example of this situation is the preparation of core samples brought up by the drill. These samples are likely to have already been divided into lengths that can be handled by the EVA crew and what ever storage system that is used to transport these samples back to the habitat. However, the customary procedure for handling cores is to divide them in half lengthwise, with one half stored as a minimally contaminated "archive" and the other half used for more detailed examination. At Mars, the crew may use this procedure for those core samples they acquire, with one half of the core sections place in the same curatorial facility as the other minimally contaminated rock and soil samples. (Note: special handling and storage may be required for these core samples if they contain volatile components that must be preserved.)

How rock and soil samples are handled and examined inside a habitat laboratory has not yet been defined in specific detail and planetary scientists have a wide range of opinions on the subject. However, it is reasonable to assume that there will be two general categories of examination and analysis that will take place — those focused on geological investigations and those focused on biological investigations. It is also reasonable to assume that, while some members of the crew will specialize in the geological or biological sciences, other members of the crew will be cross-trained to provide support in these areas, in particular, operating laboratory equipment and conducting analyses.

The majority of the geoscientist's time will be spent determining the geologic units and the contacts between the units, describing the geomorphology of the surrounding landforms and the processes that shaped them, and mapping the area around the outpost. While this is occurring, other crew members will be analyzing samples and data that the geoscientist has brought back to the habitat. Laboratory facilities to support this field work will, at a minimum, be very basic and probably include a binocular microscope for mineral identification (possibly enhanced with a reflectance spectrometer), a simple chemical analyzer (e.g., alpha proton X-ray spectrometer) for elemental classification, and simple hand-held equipment to determine a sample's physical properties (e.g., magnetism, hardness, etc.). This equipment will permit general classification of the samples and allow a reasonable judgment about which ones to transport to Earth. As time and equipment capabilities permit, more sophisticated analyses of the samples will be conducted. For example, a petrographic microscope can provide more detailed mineralogical information, including the fabric and texture of the minerals, to help determine the environment in which the rocks and minerals formed. However, this will require the ability and time to make polished thin sections. In a similar fashion,

an x-ray fluorescence system for measuring bulk rock compositions will not only permit more accurate and detailed classification of rock chemistry, but will also make possible the identification of unusual samples (*Taylor and Spudis,* 1988). More sophisticated analytical equipment may also be available as the size and power requirements of these instruments are reduced. For example, scanning electron microscopy, differential thermal analysis and gas chromatography, or Mössbauer and gamma-ray spectroscopy are all possible, and desirable, analyses that could be accomplished in a more sophisticated laboratory.

The search for chemical or physical signs of life can be accomplished in concert with the geologic examinations in the same laboratory, using some of the same instruments. Surface and subsurface mineralogical, petrological and geochemical analysis provides indispensable basic information regarding the general planetological setting of the site being analyzed, as well as the local environment and traces of biological activity (*ESA,* 1998). Life can leave its imprints at the surface of rocks as etch pits, reaction product deposits, organic matter deposits (bio-crusts) and it also can leave them underneath the surface. A search for such biomarkers has to be accompanied by the proper mineralogical and petrological characterization of the environment. Knowledge of the relative abundance of the biologically significant elements carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus, and their distribution between organic and inorganic matter is particularly important.

Examples of equipment that could be used for both geologic examinations and the search for life include:

- a binocular microscope to search the surface of rocks for the biomarkers mentioned above
- an alpha proton X-ray spectrometer to determine the light elements carbon, nitrogen and oxygen
- a scanning electron microscope to search for shapes morphologically similar to organisms on Earth and indications of biomineralization or biodegradation of minerals.

Protocols for handling samples that may be biologically active have yet to be defined and will require additional research. However, in addition to the instruments mentioned above, the crew will have several capabilities available to it that will assist with handling and analyzing these materials. The first is the nuclear reactor that is providing power to the outpost. This could be the source of sufficient radiation to sterilize any samples for which this process is deemed necessary. The same robotic vehicle used for inspection and maintenance of the reactor could also deliver the samples to an appropriate location near the reactor and return them to the habitat after an appropriate exposure period. Another facility likely to be carried within the habitat is a glovebox capable of Biosafety Level 4 containment. This glovebox is likely to be connected to the exterior by a small airlock, allowing samples to be transferred directly to the glovebox without being carried into the habitat. Such a facility will protect the crew from the sample as well as protecting the sample from the crew.

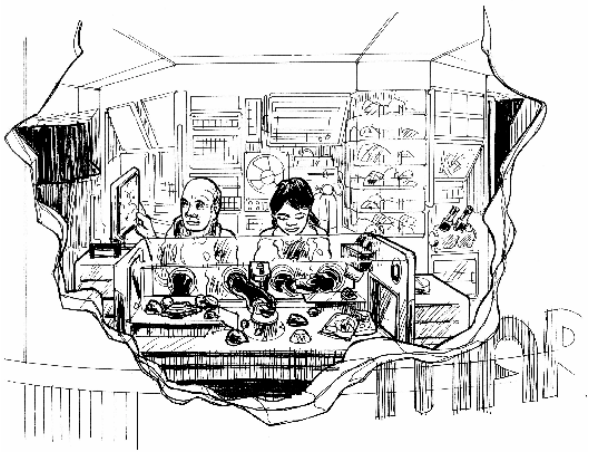


Fig. 2.8-1. Crew member examine a number of collected surface samples inside a glovebox facility. This facility will not only protect the crew from potential hazards associated with the sample, but will also protect the sample from contamination by the crew.

Data and results from all of these facilities will be stored in an on-board data system for archiving purposes. Portions of the data can be sent back to Earth to assist with the interplanetary collaboration between the crew and Earth-based colleagues as well as to disseminate some of the knowledge gain to the public.

Summary

This section has discussed the sample examination and analytical capabilities that are likely to be used on the martian surface. These capabilities are a key, distinguishing feature of these Mars missions. Two general categories of examination and analysis will take place — those focused on geological investigations and those focused on biological investigations. Having these capabilities available to them will allow the crew to better understand the environment in which they are exploring and adapt to the findings that they make, allow for collaboration with colleagues on Earth, and "high-grade" the collected samples to determine which should be returned to Earth.

There are several key areas that require additional research and definition:

- where to divide the analytical capability that is needed on Mars from that which will be brought to bear on those samples and data returned with the crew
- how rock and soil samples are handled and examined inside a habitat laboratory
- protocols for handling samples that may be biologically active.

References

European Space Agency (1998) *ESA Exobiology Science Team Study on the Search for Life on Mars.* Mid-Term Report, April 1998.

Taylor G. and Spudis P., eds. (1988) *Geoscience and a Lunar Base: A Comprehensive Plan for Lunar Exploration.* NASA Conference Publication 3070.

Treiman A. (1993) *Curation of Geological Materials at a Lunar Outpost.* NASA JSC-26194.

APPENDIX 2: LIST OF WORKSHOP PARTICIPANTS, AND EXPERIENCE RELEVANT TO MARS EXPLORATION

List of Workshop Participants

Carl Allen
Mail Code C23
Lockheed Martin
2400 NASA Road 1
Houston TX 77058
281-483-2630
carlton.c.allen1@jsc.nasa.gov

Martin Brasier
Department of Earth Sciences
Oxford University
Parks Road
Oxford OX13PR
UNITED KINGDOM
44-865-27-0274
Martin.brasier@earth.ox.ac.uk

Nancy Ann Budden
c/o Unocal Bangladesh Ltd.
14141 Southwest Freeway
Sugarland TX 77478
nancyann.budden@unocal.com

Daniel C. Burbank
Mail Code CB
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-244-8689
daniel.c.burbank1@jsc.nasa.gov

B. Clark Burchfiel
Department of Earth, Atmospheric and Planet Sciences
Massachusetts Institute of Technology
Cambridge MA 02139
617-253-7919
bcburch@mit.edu

Douglas Cooke
Mail Code EX 13
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-483-8422
douglas.r.cooke1@jsc.nasa.gov

Patricia W. Dickerson
Mail Code C23
Lockheed Martin
Houston TX 77058
281-483-4089
patricia.w.dickerson1@jsc.nasa.gov

Michael B. Duke
Lunar and Planetary Institute
3600 Bay Area Blvd
Houston TX 77058
281-244-2036
duke@lpi.jsc.nasa.gov

Bret Drake
Mail Code EX13
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-483-1806
bret.drake@jsc.nasa.gov

Dean B. Eppler
Mail Code OZ4
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-444-8216
dean.b.eppler1@jsc.nasa.gov

Jack Farmer
Geology Department
Arizona State University
Tempe AZ 85287-1404
602-965-6748
jfarmer@asu.edu

Jack Frassanito
1331 Gemini # 230
Houston TX 77058
281-480-9911
jack.frassanto@msfc.nasa.gov

Robert Garrison
Department of Ocean Sciences
University of California, SC
Earth & Marine Science Bldg
Santa Cruz CA 95064
831-459-5563
regarris@cats.ucsc.edu

Ronald Greeley
Department of Geology
Arizona State University
Tempe AZ 85287-1404
602-965-7045
Greeley@asu.edu

Ralph Harvey
Department Geological Sciences
Case Western Reserve University
112 A W Smith Bldg.
Cleveland OH 44106-7216
216-368-0198
rph@po.cwru.edu

James W. Head III
Department of Geological Sciences
Brown University
Providence RI 02912

Paul Hoffman
Harvard University
Geologic Museum
24 Oxford St Rm 230D
Cambridge MA 02138
617-495-3636
hoffman@eps.harvard.edu

Stephen Hoffman
SAIC
17049 El Camino Real Suite 202
Houston TX 77058
281-483-9264
shoffman@ems.jsc.nasa.gov

Thomas Jones
NASA Johnson Space Center
Astronaut Office
Mail Code CB
Houston TX 77058
281-483-8873
thomas.d.jones1@jsc.nasa.gov

Paul Keaton
101 Rainbow Drive, Apt 9563
Livingston TX 77351
760-321-2448
602-432-3653
pwkeaton@aol.com

Andrew Knoll
Botanical Museum
Harvard University
26 Oxford Street
Cambridge MA 02138

Jere H. Lipps
Department of Integrative Biology
University of Californian, Berkeley
3060 VLSB
Berkeley CA 94720
510-642-9006
jlipps@ucmp1.berkeley.edu

Wulf Massel
1331 Lamar Suite 605
Houston TX 77010-3037
713-650-3820
geowulf@aol.com

David McKay
Mail Code SN1
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-483-5048
david.s.mckay1@jsc.nasa.gov

William Muehlberger
Campus Mail Code 001100
Department of Geosciences
University of Texas
Austin TX 78712
512-471-4885
wmuehl@mail.utexas.edu

Timothy Parker
Mail Stop 183-501
Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena TX 91109-8099
818-354-2451
tparker@pop.jpl.nasa.gov

James Reilly
Mail Code CB
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-244-2217
james.f.reilly1@jsc.nasa.gov

James W. Rice
Lunar and Planetary Laboratory
University of Arizona
1629 East University
Tucson AZ 85721-0092
520-626-8356
jrice@lpl.arizona.edu

Bruce Runnegar
Dept. of Earth and Planetary Sciences
University of California, Los Angeles
595 Circle Drive East
Los Angeles CA 90095-1567

Harrison Schmitt
89 Juniper Hill Place, NE
Albuquerque NM 87122
505-823-2616

Paul Spudis
Lunar and Planetary Institute
3600 Bay Area Blvd
Houston TX 77508
281-486-2193
spudis@lpi.jsc.nasa.gov

Frances Westall
Mail Code SN2
NASA Johnson Space Center
Houston TX 77058
281-483-6091
frances.westall1@jsc.nasa.gov

John Young
Mail Code AC 5
NASA Johnson Space Center
2101 NASA Road 1
Houston TX 77058
281-483-3897

Experience Pertinent to Mars Exploration

AGEE, CARL B.
Chief Scientist for Astromaterials, NASA Johnson Space Center
Agee's research expertise is in high-pressure experimental petrology. The research focuses on the origin, evolution, and present state of planetary interiors. One of his current projects is an investigation of the early differentiation of the martian crust, mantle, and core. He has recently taken the position of Chief Scientist for Astromaterials at Johnson Space Center, and is coordinating JSC plans for receiving samples from Mars.

ALLEN, CARLTON C.
Planetary Geologist, Lockheed Martin/NASA Johnson Space Center
Allen is a planetary geologist with Lockheed Martin at Johnson Space Center. He earned a Ph.D. in Planetary Science at the University of Arizona with a combined field and remote-sensing study of subglacial volcanic eruptions in Iceland and on Mars. He then completed postdoctoral field studies at the University of New Mexico on subglacial eruptives of British Columbia. Switching career paths, he joined the Basalt Waste Isolation Project in Washington State, investigating the interactions of buried nuclear waste with the Columbia River flood basalts. Allen returned to the space program in Houston, and demonstrated the extraction of oxygen from lunar soils and rocks. He developed, characterized and still distributes NASA lunar and martian soil simulants. Recently he has been sampling and analyzing bacteria from Yellowstone and Hot Springs National Parks in support of JSC's Astrobiology Institute. Allen is active in the preparation for Mars sample-return missions, and is completing research on sterilization of martian samples using gamma radiation.

BRASIER, MARTIN
Paleobiologist/Paleontologist, Oxford University
Martin investigates the geological context for early biosphere evolution: time-frame and environmental setting using paleobiology, paleoecology, bio-, litho-, sequence- and chemostratigraphy, and geochronology. He is interested in innovative approaches to paleobiology; questions of interlinkage between biosphere evolution and crustal evolution. Field experience: Proterozoic paleobiology and stratigraphy in cold deserts (Gobi); hot deserts (Arabia); Proterozoic meteorite crater fill, Australia. Modern microbial/protistan habitats in lagoons, lakes. He believes in Mars-analogue field work for optimizing fossil sampling strategies. Paleontology: microfossils (textbook), microbialites, trace fossils; recent papers on origins of eukaryotes, symbiosis in protists, skeletal function in protists, multicellularity in animals (sponges), early trace fossil evolution. He believes that diverse paradigms for martian life need exploring. Laboratory experience: microfossils in thin section, disaggregation, maceration, SEM; whole rock stable isotopes using PRISM mass spectrometry; high-resolution stable-isotope studies (C, O, Sr) of carbonate and phosphate biomaterials by UV laser ablation. Chemical markers probably provide optimal clues to life, but C and O isotopic fractionation on Mars is poorly understood — high resolution isotopic monitoring is urgently needed in the field.

BUDDEN, NANCY ANN
Planetary Geoscientist, Lunar and Planetary Institute/NASA Office of Exploration (JSC)
Budden has worked for the past 10 years in the NASA/JSC Office of Exploration on human missions to Earth's Moon and Mars: (1) mission planning, (2) requirements development, (3) integration of all science disciplines, proposed programs and surface payloads. She was co-leader of the Mars Exploration Science Study Team that developed the Mars Reference Mission. She was detailed to NASA/HQ's chief scientist for a year to work on science policy for NASA. She spent five years with the Geosciences Directorate, National Science Foundation, in strategic science planning, (programs and budgets) and in developing interagency science programs among NSF, NASA, USGS, and NOAA, and DOE. She served as program scientist for the NASA/NSF Antarctic Analogs Project. Her thesis research was in paleo-oceanography of biogenic deep sea sediments

(60 Ma to present) and on tectonic/stratigraphic evolution of the Antarctic Ocean. She served as chief scientist for UNOCAL (Union Oil of California) research cruises, sampling and analyzing Miocene sediments offshore California and investigating the diagenetic history of Miocene biogenic sediments (SEM, TEM, geochemistry).

BURBANK, DANIEL C.

Astronaut/Aeronautical Scientist, NASA Johnson Space Center

Burbank was a survival instructor for the Coast Guard in Alaska — he provided classroom instruction and led week-long wilderness survival training sessions during winter on a remote island. While the course dealt with basic survival skills, a major emphasis was on the psychological aspects of survival. He was a Coast Guard helicopter pilot with more than 1,800 missions, including 300 search and rescue missions, many flown in adverse conditions. This gave him a different perspective on human performance in stressful, or even hopeless, situations. Mars exploration plans must acknowledge the limitations (physical and psychological) and the capabilities (judgement, creativity, initiative, etc.) of the human beings who are integral to those missions. He is committed to cultivating an exploration culture within NASA: "...we train excellent 'operators', and give far less attention to developing 'explorers'. And yet exploration fires people's imagination a lot better than operations ever could (and this from a career operator)." Burbank is the crew procedures lead for the flights that will deliver Node 1 (first US flight) and the US Laboratory module for the International Space Station. He is working in Moscow with Russian engineers and authors on crew procedures and on Russian ISS hardware. Astronaut training included classroom and field training in geology. A week spent in the Rio Grande rift convinced him of the importance of building a solid foundation of field research skills in the crewmembers we send back to the Moon and on to Mars. It's vital to develop and send field researchers, rather than artifact retrievers, particularly if the mission architecture places crewmembers on Mars for 500+ days. Send the necessary instruments to begin analysis, or at the very least to make proper specimen selection.

BURCHFIEL, B. CLARK

Field Geologist/Tectonist, Massachusetts Institute of Technology

Burchfiel is a field geologist who investigates the processes of orogenesis and their relation to plate interactions and intra-plate deformation. His major research efforts are in five areas: (1) the Cordilleran orogenic belt of western North America, (2) Alpine belt of Eastern Europe, (3) the Caledonian belt of Scandinavia, (4) the Andean belt in Peru, Bolivia, and Colombia, and (5) north-central China and Tibet. His research focuses on processes of intracontinental deformation. It is designed to examine orogenic belts and other regions of significance within the continents of different ages, tectonic settings, and hence at different levels of exposure. The Alpine and Caledonian belts are collisional orogens, whereas the Cordilleran belt and Andean belts are partly noncollisional. The work in China is a study of neotectonics in active orogenic belts: normal faulting in the High Himalaya and the tectonic evolution of the Tibetan Plateau, Tien Shan and southeastern Asia. The eastern Alpine studies also include extensional regions coeval with convergence during a precollisional stage. He attempts to solve specific problems or develop conceptual models from field mapping integrated with geophysical and geodetic studies and, where relations permit, to attack mechanical problems on a theoretical basis.

DICKERSON, PATRICIA WOOD

Field Geologist-Geophysicist, Lockheed Martin/NASA Johnson Space Center

Dickerson is engaged in field and classroom training of astronauts/cosmonauts in tectonics and geomorphic analysis; creation of electronic handbooks on global tectonics is an aspect of that instruction. Her research emphasis has been on continental and oceanic rifts and transforms: global patterns in tectonic geomorphology, volcanism, and sedimentation, both temporal and geometric. Comparative studies, especially of Rio Grande and western East African rifts and transforms, have included remote sensing, geophysical, and field structural analyses. Investigations of transform faults have included physical modeling of strike-slip deformation. In the context of Quaternary faults and dating of fault activity, she has developed an isotopic/palynologic technique for determining timing of fault movement through analysis of spring deposits. Other investigations have been in contractional orogenic zones: Ouachita, Laramide (New Mexico through Mexico), the Argentine Precordillera,

north Norwegian Caledonides. She has collaborated in developing and field-testing shallow-penetration seismic instruments and has explored for resources (water, gold, petroleum) in various remote and rigorous environments.

EPPLER, DEAN B.
Field Volcanologist/Spacesuit Test Subject, SAIC, NASA Johnson Space Center
Eppler is presently the prime space suit test subject for advanced planetary EVA system development. He received a B.S. in Geology from St. Lawrence University in 1974, M.S. in Geology from the University of New Mexico in 1976, and Ph.D. in Geology from Arizona State University in 1984. His research has included extensive field work in volcanology and geomorphology in such diverse environments as the Dry Valleys of Antarctica, the interior deserts of Iceland, the Cascade volcanic range in California, and the Rio Grande rift in northern New Mexico. Eppler's work with the advanced EVA system development group has been focused on identifying those elements of EVA suit mobility that are key to the conduct of field geology, and on testing various EVA suit/backpack configurations in the conduct of geologic field work in terrestrial terranes and topographies that are analogs to the lunar and martian environments.

FARMER, JACK
Geologist/Paleontologist, Arizona State University
Farmer is a geologist/paleontologist by training and has field experience in a variety of terrains including Alaska, Arctic Norway, Antarctica, Australia, Mexico, and the deserts of the southwestern U.S. He has also worked at the Ries impact crater site in Germany and in basaltic terrains of Iceland. His recent Mars analog studies have focused on Yellowstone, Wyoming, and on the terminal lake systems of the Great Basin, including Mono and Pyramid Lakes, Nevada. He has participated in several Marsokhod rover trials including Amboy Crater (Mojave), Kilauea, Hawai'i, and most recently on Hopi Lands in northern Arizona. He participated in the JPL Rocky 7 trials at Lavic Lake (Mojave) and will also be involved with the upcoming NASA Ames Marsokhod trial (February, Mojave) and the JPL FIDO trial (successor to Rocky 7) to be held next spring. From the mission-planning standpoint, he have been on many teams in the past 10 years, including the Mars Global Surveyor 2001 Science Definition Team. Currently he is involved with the Mars Expeditions Strategy Planning Group (MESG) at JPL and is a member of the Solar System Exploration Subcommittee (SSES) at NASA Headquarters. He is also lead for ASU-funded astrobiology activities carried out through the NASA Astrobiology Institute; along with 11 other PIs, he is a member of the Executive Board of the Astrobiology Institute.

GARRISON, ROBERT E.
Sedimentologist, University of California at Santa Cruz
Garrison is Professor Emeritus of Earth and Ocean Sciences, University of California at Santa Cruz. His geological interests are in the sedimentology and diagenesis of fine-grained and highly organic sediments. He has carried out field and analytical studies of these kinds of deposits in California, the Middle East, and South America, along with investigations of sediment cores retrieved from the coastal upwelling zones along the Perú margin and in the Mediterranean. Specific interests include the origin of microbially generated sedimentary phosphorites, the formation of authigenic carbonates as a consequence of degradation of organic matter, and sedimentary structures as indicators of paleoenvironments and diagenetic processes. He participated in petrological and electron microscopic studies of lunar samples returned by Apollo 12.

GREELEY, RONALD
Planetary Geologist, Arizona State University
While a research scientist at NASA-Ames Research Center, Greeley was involved in (1) pre-Apollo lunar surface geological studies, (2) field studies of terrestrial analogs for the Moon, (3) wind-tunnel simulations of Mars sand/dust storms, (4) Mars-Mariner 9 data analysis, and (5) site selection for theViking mission. He has been affiliated with Arizona State University since 1978 and has conducted (1) studies of volcanic rocks and geology for the Viking extended mission, (2) field analog studies of Iceland, Hawai'i, Mt. Etna, Bolivia, (3) Mars 94 preparation, (4) Mars landing site analog studies, (5) Mars rover

tests in the Mojave Desert, at Kilauea volcano, and in the Painted Desert, and (6) studies for the Mars Pathfinder mission. In addition, he has organized NASA field conferences in Hawai'i, the Snake River Plain, and the Mojave Desert; he has chaired a NASA study on Evolution of Climate and Atmosphere of Mars; he has chaired a National Academy of Sciences Committee on Lunar and Planetary Exploration; and he is co-author of the *NASA Atlas of the Solar System.* Greeley was a micropaleontologist with Standard Oil of California before becoming involved in lunar and martian investigations.

HARVEY, RALPH P.

Petrologist — Martian Meteorites, Case Western Reserve University

Harvey is Principal Investigator and Field Team leader for the Antarctic Search for Meteorites (ANSMET) project (funded by Office of Polar Programs, NSF). He has led eight and participated in two 45-day-long field seasons, operating under conditions of hostile climate, significant isolation, and complete self-sufficiency. He is a Principal Investigator in the NASA Ancient Martian Meteorite program, and long-time researcher on martian meteorites in general. Ralph has produced a wide variety of publications on martian meteorites, including several on ALH84001, focusing on igneous petrology and its relevance to the history and environment of Mars. Other field experience includes geochemical and petrologic studies of basaltic rocks in Iceland, northern Ontario, the Appalachians and New Zealand, and studies of micrometeorites in aeolian sediments, salt deposits, and polar ice. Laboratory research typically involves study of mineral chemistry and texture by means of electron microprobe, transmission electron microscope and scanning electron microscope.

JONES, THOMAS D.

Astronaut/Planetary Scientist, Johnson Space Center

Jones earned his Ph.D. in planetary science from the University of Arizona. His research interests included the remote sensing of asteroids, meteorite spectroscopy, and applications of space resources. He was a program management engineer at the CIA Office of Development and Engineering. While with Science Applications International Corp., he performed advanced program planning for the NASA Solar System Exploration Division, investigating future robotic missions to Mars, asteroids, and the outer solar system. Prior to pursuing doctoral work, Jones graduated from the U.S. Air Force Academy and served as an Air Force pilot, having commanded the combat crew of a B-52D Stratofortress. Jones has logged over 40 days (963 hours) in space. He flew as a mission specialist on successive flights of *Endeavour* (STS 59 and STS 68), both of which demonstrated advanced synthetic aperture radar technology (Space Radar Lab) in investigations across the range of the Earth sciences. On STS 80, while helping set a shuttle endurance record of nearly 18 days in orbit, he used the robot arm of Columbia to release the Wake Shield satellite and later grapple it from orbit. Jones is now chief of the Astronaut Office Station Operations Branch, helping plan the construction and operation of the International Space Station. He is assigned to fly next on Space Station Assembly Mission 5A, STS-98, scheduled for early 2000. The *Endeavour* crew will deliver the U.S. laboratory module to the space station; Jones will help install the lab with a series of three spacewalks. He hopes that success with ISS will lead quickly to long-duration missions beyond low-Earth orbit.

LIPPS, JERE H.

Field Paleontologist/Marine Biologist, University of California, Berkeley

Lipps is a field paleontologist and marine biologist, who has worked extensively in both disciplines (also in field geology) at sites all around the world since 1960. He has taught field geology, paleontology and marine biology at sites in California, Nevada, and French Polynesia. Paleontologic sites for research include East Africa (Pleistocene hominid-bearing lakes), White Sea of Russia (Vendian fossils), Western U.S. (Tertiary, Mesozoic, Paleozoic, and Precambrian fossil-bearing marine seds), Australia (Precambrian of the Kimberleys), Siberia (Vendian, Cambrian), Kazakhstan (Cambrian), Papua New Guinea (Pleistocene reefs, Eocene sediments), and Hawai'i-Tahiti (Deep Sea Drilling Project Leg 8). Marine biology research sites include Antarctica (Palmer Station, McMurdo, and Ross Ice Shelf), Enewetak Atoll, Papua New Guinea (Papuan and Madang Lagoons), French Polynesia, California and Baja California, Lizard Island (Great Barrier Reef), Bimini, Palau, and others where he studied living invertebrates and foraminifera for comparison to, and understanding of, fossil organisms.

MASSELL, WULF

Field Geophysicist/Petroleum Explorationist, Epic Geophysical Co.

Massell has operational seismic crew and equipment experience in swamps, deserts, jungles, and polar plateaus and has worked for more than a year in Antarctica. He is familiar with most near-surface geophysical methods and, while on the faculty at the University of Texas-Austin, Wulf established the first geophysical field-methods course offered by the Department of Geological Sciences. He has conducted geologic mapping in the Rocky Mountains, the Mid-Continent (flat rocks), and in the Big Bend of west Texas. In support of survey planning he has carried out photo reconnaissance work for near-surface geological, geomorphological, and hazards studies. He has some familiarity with remotely operated (downhole) tools and data, including well logs. Massell now specializes in processing data from 2-D and 3-D seismic surveys as applied in petroleum exploration. The volume of 3-D seismic data can be so large (tens of gigabytes) that data compression schemes are now under development; such techniques will be important in transmitting seismic data from Mars. While working in Antarctica, Massell directed some thought toward selection criteria for a team that might travel to Mars and back.

MUEHLBERGER, WILLIAM R.

Field Geologist/Tectonicist/Astronaut Instructor, The University of Texas at Austin

Muehlberger and his students have made geologic maps of many regions of Central and North America, the Dead Sea fault zone in Turkey, and of the Moon. Lunar mapping included the fold belts on the mare surfaces; an interpretation of the tectonic history of the Apollo 17 landing site accompanied maps of the area. Bill has been involved in geological training of astronauts since 1964: He was Principal Investigator of the Apollo Field Geology Experiment for Apollo Missions 16 and 17, in addition to serving as co-investigator for the Earth Observations Experiment for Skylab 4 and the Apollo-Soyuz mission. Since inception of the Space Shuttle program, he has been part of the Earth Observations team at Johnson Space Center, and he has now begun training crews for International Space Station.

RICE, JIM

Astrogeologist, University of Arizona

Rice is a member of the Imaging Team of the ’98 Mars South Polar Lander at the Lunar and Planetary Laboratory at the University of Arizona. He specializes in martian periglacial, fluvial, and lacustrine geomorphology and is currently working on the fluvial geomorphology and history of the Mars Pathfinder landing site. He is also involved with landing site selection for the ’98 Mars South Polar Lander and 2001 Mars Surveyor Lander. Rice has also been a field team member on Mars rover tests and worked on a Manned Mars Mission Study at Marshall Space Flight Center. Rice has conducted Mars analog field investigations in the Antarctic, Arctic, Iceland, Channeled Scabland of Washington, and the deserts of Arizona, California, and Mexico. He was a member of the first joint NASA/Russian expedition to the ice-free regions of eastern Antarctica. He spent six months on this joint scientific expedition where he conducted geologic and geomorphic field investigations and was also a Research Diver on the SCUBA Diving Team, which explored the ice covered lakes of this region. Rice has spent the last two years conducting field investigations at the Haughton impact crater on Devon Island in the High Arctic. This summer he’ll conduct further field work in both the Haughton impact crater and Iceland.

SPUDIS, PAUL

Planetary Geologist, Lunar and Planetary Institute (Houston)

Spudis is a geologist who received his education at Arizona State University (B.S., 1976; Ph. D., 1982) and at Brown University (Sc.M., 1977). Since 1982, he has been a Principal Investigator in the Planetary Geology Program of the NASA Office of Space Science, Solar System Exploration Division, specializing in research on the processes of impact and volcanism on the planets. He has served on NASA’s Lunar and Planetary Sample Team (LAPST), which advises on allocations of lunar samples for scientific research, the Lunar Exploration Science Working Group (LEXSWG), that devised scientific strategies of lunar exploration, and the Planetary Geology Working Group, which monitors overall directions in the planetary research

community. He has also been a member of the Committee for Planetary and Lunar Exploration (COMPLEX), an advisory committee of the National Academy of Sciences, and the Synthesis Group, a White House panel that in 1990–1991 analyzed a return to the Moon to establish a base and the first human mission to Mars. He was Deputy Leader of the Science Team for the Department of Defense Clementine mission to the Moon in 1994. He is the author or co-author of more than 100 scientific papers and two books, including his most recent, *The Once and Future Moon,* which was published in the Smithsonian Library of the Solar System series for the general public.

WESTALL, FRANCES

Micropalaeontologist/Exobiologist, NRC-Johnson Space Center

Westall's principal expertise is in the field of fossil bacteria and bacterially produced biofilms. She is experienced in working with the modern microbial environment (shallow- to deep-water marine environments, among others) and with biofilm formation in nature and in the laboratory. She has conducted research in the experimental fossilization of bacteria. Westall has studied fossil bacteria and biofilms from different parts of the rock record, representing different types of microbial environments: (1) silicified marine bacteria and biofilms from the Early Miocene (South Atlantic Ocean); (2) phosphatized bacteria from a reducing volcanic lake, Early Eocene (southern Germany); (3) silicified bacteria and biofilms from the 3.3 to 3.5 Ga Early Archean terrains of the Barberton greenstone belt, South Africa, and the Pilbara Craton, Australia.

APPENDIX 3: WORKSHOP COMMUNICATIONS, AGENDA, AND DISCUSSION OUTLINES

LUNAR AND PLANETARY INSTITUTE
3600 Bay Area Blvd., Houston, Texas 77058-1113 USA

Dear Colleague: October 28, 1998

NASA has been studying the possibility of sending a human expedition to Mars. Although there currently are no programs in place to do so, within the next decade it is possible that development of human missions will begin. In recent studies, a concept has been favored in which a crew of several people (~6) would be on the surface of Mars for about 500 days. Their primary function would be to conduct field investigations to address the questions of martian geological and biological evolution. The Reference Mission description (NASA SP-6107) is available on the World Wide Web at

http://exploration.jsc.nasa.gov/EXPLORE/explore.htm. or http://www-sn.jsc.nasa.gov/marsref

No coherent concept for the geological/biological exploration of Mars by humans has been developed, beyond general considerations. We would like to request your help in furthering our understanding of the opportunities and issues that NASA will have to address in preparing to send humans to Mars for these purposes. To start the process, we are convening a 2-day workshop at the Lunar and Planetary Institute on November 18-19, 1998. Dr. David McKay of the Johnson Space Center and I will be the co-convenors. A preliminary list of topics is attached. The list of invitees is small and has been selected to represent people with diverse field experience on Earth, rather than experience in space exploration. We hope that this will give us a good start, but we anticipate that much additional work will be needed.

If you are able to participate in this meeting, the Lunar and Planetary Institute will provide your travel and subsistence expenses. Ms. Sharon Steahle (281-486-2166) will be the point of contact, and will provide the necessary information.

I hope that you will be able to join us on November 18-19. Please let us know by email to Nancy Ann Budden at the Lunar and Planetary Institute (budden@lpi.jsc.nasa.gov, or by phone at 281-244-2051). If you have questions, please call me at 281-244-2036 or Dave McKay at 281-483-5048.

Sincerely,

Michael B. Duke

Attachment (1)

Mars Field Geology, Biology and Paleontology Workshop
November 18-19
Lunar and Planetary Institute
Houston, Texas

The purpose of this workshop will be to explore the objectives, desired capabilities, and operational requirements for the first field exploration of Mars. Current NASA planning envisions sending a crew of six people to Mars, as early as 2013, to conduct detailed exploration of a site on Mars. The crew will spend a year and a half on Mars and will have considerable mobility, sampling, and analysis capability, in an area of high scientific interest. The major objectives of this exploration will be to continue investigations of Mars' biological history, through geological and paleontological investigations and analysis of potential pre-biotic chemistry. The search for extant martian organisms in isolated environments, requiring deep drilling, is a likely objective.

The preliminary agenda includes:

An overview of NASA mission planning for human exploration of Mars will be provided.

a. Science objectives
b. Mission planning

Discussions on several major topics:

a. What are appropriate approaches to field geological/biological investigations?
    1. What prior information should be gained/assumed?
    2. What should the strategy be in the field?
    3. Are there significant differences between geological, paleontological or biological fieldwork?
    4. How can astronauts best work in the field on Mars?
    5. What tools are needed?
    6. What is the appropriate allocation of time between tasks?
b. How much analytical capability should be provided on Mars?
    1. In the field
    2. In a laboratory
    3. How should the field/laboratory work be coordinated?
c. What are the implications for crew skills and training?
    1. Primary scientific crew members
    2. Backup and associate scientific members
d. How should communications be structured between the crew on Mars and scientists on Earth?
    1. Science planning
    2. Support of crew observations
e. How should discussions on this topic be continued?
    1. Workshops
    2. Analog studies
    3. ?

LUNAR AND PLANETARY INSTITUTE
3600 Bay Area Blvd., Houston, Texas 77058-1113

November 2, 1998

Dear Mars Field Geology, Biology, and Paleontology Workshop Participant:

Thank you for agreeing to attend and support the Mars Field Geology, Biology and Paleontology Workshop scheduled for November 18 and 19, 1998 at Space Center Houston, in Houston Texas. The meeting promises to be both intriguing and challenging as we address the timely subject of how human crews could most effectively explore, study, and return samples from the surface of Mars.

We have had an overwhelming response to the meeting, and participants from many different science disciplines will be co-mingling their ideas and experiences. In our two days together we will journey from the past, to the present, to the future. We will embark on our adventure with Jack Schmitt, the geologist who walked on and explored the moon during Apollo 17, the last human mission on the lunar surface. Next Bret Drake and Steve Hoffman from NASA/JSC's Exploration Office will review the Mars Reference Mission, and a work-in-progress, the Mars Surface Reference Mission. Steve Saunders, JPL program scientist for Mars Global Surveyor, will present the latest findings on Mars geology from Mars orbit. The final invited presentation is from Dean Eppler of the NASA/JSC EVA office, who will take us into the future with the new Mars Space suit, and discuss the challenges and limitations of conducting geologic field work in a pressurized suit.

The remaining portion of the meeting will be spent discussing specific topics and issues, first with all the workshop participants, and later in small teams. The anticipated product of the workshop is a publication (possibly EOS), documenting our discussions and conclusions. It is our hope that most of the writing will be accomplished on the second day of the workshop. A brief outline of each discussion topic along with its discussion leader is included in the agenda.

This will be the final mailing before the meeting. Enclosed please find the preliminary agenda, and some background articles and excerpts to provide everyone a common base of knowledge. Be reminded that the entire Mars Reference Mission document (NASA SP-6107) can be found at: http://www-sn.jsc.nasa.gov/marsref

Meeting attire is casual, as is our dinner on Wednesday November 18 at Villa Capri. Our fall evenings can be cool, so bring a sweater. If you have a laptop, particularly one equipped with Office 97, please bring it. For first-time visitors to Houston, be advised that Space Center Houston is a not-for-profit organization distinct from NASA Johnson Space Center. It is located adjacent to, and just before NASA/JSC, on NASA Road One.

Travel and logistics queries should be made to Ms. Sharon Steale at (281) 486-2166. Questions dealing with the content of the meeting should be addressed to Nancy Ann Budden at 281-244-2051 or budden@lpi.jsc.nasa.gov.

Best regards,

Michael B. Duke	David S. McKay	Nancy Ann Budden
Lunar and Planetary Institute	NASA/JSC	Lunar and Planetary Institute

Final Agenda

Mars Field Geology, Biology and Paleontology Workshop
Space Center Houston, Saturn Club, Houston, Texas
November 18 and 19, 1998

Mike B. Duke, David S. McKay, William R. Muehlberger, Nancy Ann Budden, conveners

Wednesday, November 18, 1998: Space Center Houston, Club Room

8:00	*Continental Breakfast*	
8:30	Welcome and Introduction	David McKay, NASA/JSC
8:45	Meeting Objectives and Schedule	Nancy Ann Budden, LPI
9:00	From Apollo to Mars: History and Vision	Bill Muehlberger, UT Austin
9:15	Apollo 17: Field Geology on the Moon	Jack Schmitt, Interlune
9:45	Mars Reference Mission	Bret Drake, NASA/JSC
10:15	*Coffee Break*	
10:30	Mars Surface Mission	Steve Hoffman, SAIC
11:00	Mars Geology: The Newest Data	Tim Parker, NASA/JPL
11:30	EVAs on Mars: Challenges of the Next-Generation Space Suit	Dean Eppler, SAIC
12:00	*Lunch, Space Center Houston Cafeteria*	
1:00	Discussion: Approaches to Field Strategies	Bill Muehlberger, lead
3:00	Discussion: Analytical Capabilities	Frances Westall, lead
6:00	*No-host dinner, Villa Capri, NASA Road One*	

Thursday, November 19, 1998: Space Center Houston, Club Room

8:00	*Continental Breakfast*	
8:30	Plan for the Day	Nancy Ann Budden
8:45	Discussion: Crew skills and training	Tom Jones, discussion leader
10:30	Discussion: Communications between Mars-Earth	Pat Dickerson, discussion lead
12:00	*Lunch, Space Center Houston Cafeteria*	
1:00	Team Discussions and Team Writing	All
3:30	Team Responses: Top 3 Recommendations	Discussion Leaders
4:30	Final Discussion and Assignments	Budden
5:00	*Adjourn*	

Outlines for Discussions and Sections for Final Mars Field Geology, Biology, and Paleontology Article

I. Discussion One: Bill Muehlberger, discussion leader

1. What are appropriate approaches to field geological/biological investigations?
2. What prior information should be gained/assumed?
3. What should the strategy be in the field?
4. Are there significant differences between geological, paleontological and biological field work?
5. How can astronauts best work in the field on Mars
6. What tools are needed? (See Discussion Two)
7. What is the appropriate allocation of time between tasks?
8. How should discussions of this topic be continued?
    - Are workshops an effective mechanism?
    - Can analog experiments provide a useful focus for discussions?
    - Should a formal working group be convened for defining requirements for NASA?
    - Are specific projects or studies indicated?

II. Discussion Two: Frances Westall, discussion leader

How much analytical capability should be provided on Mars?

1. In the field
    - Strategic considerations
        - distance from base camp
        - likelihood of returning to sample site
    - Level of analytical capability
        - none
        - rock discrimination
        - in-situ analysis
        - high grading and return to Mars base

2. In a Mars-based laboratory
    - Types of analysis
    - Allocation of time to analysis
    - Miniaturization, new technologies

3. How should the field/laboratory work be coordinated?
    - Specialization
    - Feedback into field expedition planning

4. Selection of materials for return to Earth
    - Types of preliminary analyses
    - Sample curation on Mars

5. How should discussions of this topic be continued?

    - Are workshops an effective mechanism?
    - Can analog experiments provide a useful focus for discussions?
    - Should a formal working group be convened for defining requirements for NASA?
    - Are specific projects or studies indicated?

III. Discussion Three: Tom Jones, discussion leader

What are the implications for crew skills and training?

1. What scientific skills area needed?
    - Field Geology
    - Biology
    - Paleontology
    - Analytical
    - Computing
    - Communications

2. Can priorities be established?

3. What training environments are most important?
    - Terrestrial analogs
    - Virtual environments
    - On-site training

4. What techniques for maintaining science skills seem most important?
    - Videotraining
    - Lectures/Discussions
    - Field camps

5. What constraints will be placed on operations by skill mix?

6. How should discussions of this topic be continued?
    - Are workshops an effective mechanism?
    - Can analog experiments provide a useful focus for discussions?
    - Should a formal working group be convened for defining requirements for NASA?
    - Are specific projects or studies indicated?

IV. Discussion Four: Pat Dickerson, discussion leader

How should communications be structured between the crew on Mars and scientists on Earth?

1. What should be the principal objectives for communications between astronauts on Mars and scientists on Earth?

2. What is the desired level of autonomy of crew members on Mars?

3. How much time typically should be allocated by the crew for science planning?

A. Pre-Mission Science Planning
   a. Briefings by NASA staff, visiting researchers/PIs, crew scientists
   b. Field Training
      i. Exploration methods (biological/geological/geophysical methods, considering portability, crew dexterity, EVA limitations)
      ii. Use of robotic field assistants
      iii. Field documentation (photographic methods, systematic oral description/transcription, sampling

B. Science Planning and Changes During the Mission
   a. What strategies can be used to optimize support by scientists on Earth?
   b. Utilization of rotating teams of ground-based research specialists responsible for following mission segments, conducting regular crew debriefings/"discussions" via radio, e-mail exchanges of "batched" data

4. The Forty-Minute Lag — How can real-time changes in strategies and plans best be implemented?

A. Eureka!! experiences
B. Research scientists on-call

5. What equipment should be considered for optimizing communications between astronauts in the field and at base camp and collaborators on Earth?

6. How should discussions of this topic be continued?
   A. Are workshops an effective mechanism?
   B. Can analog experiments provide a useful focus for discussions?
   C. Should a formal working group be convened for defining requirements for NASA?
   D. Are specific projects or studies indicated?

APPENDIX 4: STRAWMAN SCIENCE PAYLOADS AND FEASIBILITY STUDY

Feasibility Study

Most of the equipment discussed above is deemed to be essential for basic field exploration and basic laboratory examination. With the exception of the rovers, utility truck and drill, much of it is already in miniaturized form or is being developed as such for robotic missions and would, therefore, be available in the future. The capability of deeper drilling would be increased with successive missions and laboratory instruments.

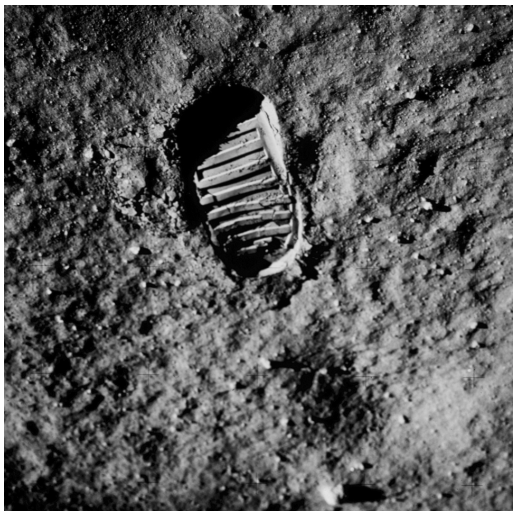
Some indication of the payloads involved can be obtained from the following studies and adapted below: (1) Hoffman et al. (1997) *The Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team,* NASA Special Publication #6107; (2) ESA (1998) *ESA Exobiology Science Team Study on The Search for Life on Mars*; (3) Budden N. A. (1994) *Catalog of Lunar and Mars Science Payloads,* NASA Reference Publication #1345.

Strawman Analytical Payloads	Payload Mass (kg)
Field geology package (geologic hand tools, cameras, sample containers, documentation, instrumentation)	350
Geology laboratory (microscopes, camera, geochemical instrumentation, dating instrumentation)	150
Biology laboratory (microscopes, culturing facilities PCR, plant growth experiment)	600
Geophysical mapping instruments	400
10 m drill	260
Meteorology balloons	200
Total	1960 kg

The ESA report (1998) gives a breakdown of the payload for instrumentation on a robot and lander from which the following list is adapted:

Strawman Rover Payloads	Payload mass (kg)
Robotic positioning arm	2.0
Rock surface grinder	0.4
Low power microscope	0.2
Small rock coring drill	3.5
Core sample containers	0.5
Subsurface drill system	6.5
APX spectrometer	0.5
Mössbauer spectrometer	0.5
Laser Raman spectrometer	1.5
Pyrolitic GCMS	5.5
Oxidant detector	0.4
Laser ablation ICP-MS	2.5
Total	24.4 kg

APPENDIX 5: MARS MISSION QUESTIONS: RALPH HARVEY



THREE BIG QUESTIONS AND 150 LITTLE QUESTIONS

What follows is an independent collection of questions that one might ask about Mars. They were assembled by workshop participant Ralph Harvey just before deploying to the dry valley region of Antarctica in December 1998.

Big Question 1: Why Explore Space at All?

Because the future, and the entire universe, lie out in front of us. Thinking, knowing, curious beings like ourselves cannot help but wonder what is out there. It is far better to take willing, well considered strides into that future, into that universe, than to wait passively for the tides of time to take us there.

Big Question 2: Why Go to Mars?

What we currently know about Mars strongly suggests that many of the geological, environmental and perhaps even biological processes that have shaped that planet are similar to those active within the Earth's history as well. At the same time, these processes clearly took place on different geographical and temporal scales on Mars. Exploring Mars, and the differences between Mars and Earth, allows us to explore these processes much more fully than can be done from a single planetary example; in turn, they help establish the relative uniqueness of our own planet. From a practical standpoint, Mars has a surface environment similar enough to Earth's that we can realistically envision ourselves living off the land to some degree, making exploration easier and more familiar.

Big Question 3: Why Send Humans to Mars?

The human mind is amazingly good at detecting the key elements in an otherwise overwhelming pile of data: spotting in an instant what is out of place, unique, unusual, or key to a given scenario. While this skill is the product of millions of years of evolution, helping us hunt and avoid danger, today it serves the scientist in a way that robotic intelligence or remote sensing cannot: by allowing a scientist to quickly develop a likely hypothesis for what he or she sees, grasping the key elements that make a given scenario unique, without laboriously building that scene from data, pixel by pixel. Obviously there's a danger there; shortcuts are risky. But for the experienced scientist they inevitably pay off, and false trails can be quickly left behind.

And only experience allows one to build the internal catalog of knowledge that predicts what should be seen, and what shouldn't.

Nowhere in the realm of science is the human ability to integrate a scene quickly and identify key features more vital than in geology, and geology forms the baseline for much of what we want to know about Mars. Understanding the geology of Mars means reading the rocks and the history of the planet that they record; but the language of the rocks is a difficult and derivative one and it requires years of learning and practice to achieve fluency. The typical field geologist must be able to identify several hundred types of rocks, and the several hundred different minerals that may make them up; they must be able to read the signs that suggest alteration by weathering, the movement of fluids, the influences of heat and pressure, or biological activity may have produced what is being seen. As a result, the very best geologists are the ones that have built up substantial and diverse catalogs of observations that they can apply to any new scene they encounter.

MORE THAN 150 QUESTIONS ABOUT MARS GEOLOGY

The questions below are a response to the questions: "Why do I want to go to Mars?" "What do I want to know about that planet?" "What questions do I have personally that only going to Mars could answer?"

Having generated these questions personally, they might be considered a testimony to my own ignorance, but I hope they will also serve to illustrate our deep lack of ground truth concerning the geology of Mars. Many of these questions have tentative answers, or can be explored through remote observations, but none have definitive answers. On the other hand, many of them could be solve literally in minutes or hours by a well trained geologist in the right place on the surface of Mars. Please note that none of these questions directly address paleontology or biology. Given that there is NO positive evidence for either on Mars, the list of possible questions on these topics is virtually endless!

- What are the southern highlands composed of (what rock type)? Are they the ancient crust of Mars? Are they of uniform age? Are they of uniform composition?

- What does the age and compositional uniformity (or lack of it) tell us about early martian history?

- What is the age of the big basins (Hellas and Argyre)? How does the cratering rate at Mars compare to theoretical models or those computed from other terrestrial planets?

- What is the "intercrater" material of the southern highlands (volcanic, sedimentary, ejecta)? How old is this "intercrater" material? Is it of uniform age? How deep is the regolith of Mars in the southern highlands, and how well lithified?

- When did the ancient drainages in the southern highlands form? Are they all of one age, or do they span a longer period of martian history? What processes formed them; is there direct evidence of precipitation? Is there direct evidence of groundwater sapping? How much sediment did they move? Did that sediment form consolidated rock? What was the source of the water that formed them? What was the composition of that water? Where did the water go? Did the big basins fill with water? How long was water present on the surface in the highlands? Are there features such as shorelines, evaporites, bars and spits that point toward active fluvial and lacustrine processes?

- What kind of volcanic processes were present in the Southern Highlands? Are Tyrrhenia Patera and the other highly dissected volcanos of a common type? What types of volcanic rocks did they produce? When were they active? Do they represent a style of eruptive activity unique to the region, or to a specific period in martian history? How are

they related to the ancient martian crust in the region? How are they related to the martian Mantle and the typical volcanics of Mars' northern hemisphere? Why are they physically so different? What secondary processes eroded them down to their present shape? Was there involvement of significant volatiles in their eruption, or secondary erosion?

- Why is the scarp that separates the Southern Highland from the Northern Plains so sharp? When did this scarp form? What processes formed it? How has it been altered since formation? What ancient rocks are exposed in this scarp?

- How uniform are the soils of Mars? What minerals are they made up of, and what are their sources? What distinguishes light and dark soils, and why do they have different aeolian transport properties? Are there really no organics present at all, and why? Are there "hyperoxidants" present that destroy organics, and if so, what are they and how did they form? How long has aeolian soil been forming, and at what rate? What processes (sedimentary, aeolian, etc.) are primarily responsible for their production? Do they become indurate or consolidated? By what processes?

- What are the polar layered deposits made of? How are they related to the polar ice caps? Do they contain frozen volatiles, and if so, what is its composition? What is the composition of the ice caps? What is the composition of entrained dust and rock in both deposits? Do these deposits flow, and if so, at what rate? How old are they? What accumulation and loss mechanisms are active? How do they interact with the martian climate on daily, seasonal, and epochal timescales? How do they interact with the martian crust (groundwater, chemical alteration, etc.)?

- What processes formed the Valles Marineris? When did it form? What distinguishes it from other regional tectonic features? Is uplift in the Tharsis region truly responsible for its orientation? What role has mass wasting played in its history? What role has groundwater sapping played? What role has fluvial activity played? What instigated its formation, and the later alteration processes? What rocks are found within the exposed stratigraphy there? Is the full history of the martian crust exposed, from most ancient crust to modern volcanics? Is there any evidence for unconformities? Is there any evidence for rotational or strike/slip movement of the crust?

- What are the ages of the Tharsis volcanics? What compositions of volcanic material did they produce? What produced the scarp around the base of Olympus Mons and what is its significance? Are the four large Tharsis volcanoes distinct in terms of ages and composition, or are they all products of a single "event"? How do they relate to surrounding flood basalt deposits? How do they relate to smaller volcanoes to the east and south? What is the full sequence of eruptions, in terms of time and lithologies? What does this sequence tell us about crustal activity on Mars? How do the Tharsis volcanics relate to the tectonic deformation of that region? What does this sequence tell us about the thermal history of Mars?

- What is the age of Alba Patera? What volcanic or igneous processes produced this unique volcanic feature? How does it relate temporally and compositionally to the other local volcanics? Could it be the source of volcanics for hypothetically resurfacing the Northern Plains?

- What is the age of the Elysium region volcanics? Are they distinct compositionally and temporally from the Tharsis volcanics? Are the lithologies that built up Elysium Mons "evolved" as the profile of that volcano would suggest? How are the volcano lithologies related to the flood basalts of the Elysium plains? Why is the pattern of tectonic deformation associated with Elysium distinct from that seen in Tharsis? Why are there "sapping" and drainage features associated with Elysium but not with Tharsis?

How do the styles of intrusive and extrusive volcanism seen on Mars compare to those seen on Earth, and those seen in the martian meteorites? Can we identify the places that material similar or identical to the shergottites, nakhlites, lherzolites, chassignites, and ALH84001 are found on Mars? What is their context in the volcanic history of Mars?

- Is there presently a water table on Mars? Is there presently permafrost on Mars? What is the distribution of these volatile reserviors on global and regional scales? What is the distribution of these volatiles in terms of depth? What is the present size of these reserviors? What is the composition of these reserviors? How do these reserviors interact with the current climateof Mars? How did they interact on ancient Mars? Has Mars ever had a hydrologic cycle, and if so, how recently? How much water did ancient Mars have? How much does it have now? What accounts for any differences?

- When did the massive floods that produced the Ares Valles and other outwash channels occur? Were these single events, or multiple events? How long did they last? What processes triggered these floods, and why in these specific areas? Were any significant bodies of standing water or ice produced, and how long did they last? How did these floods interact with the climate of Mars over short and long term timescales?

- Have any sedimentary rocks been produced on Mars? How have martian environmental conditions controlled the type of weathering and the sediments produced? How much transportation of sediment occurred, and in what style? What diagenetic processes are or were active on Mars to consolidate this sediment? Is there a sedimentary rock record on Mars and what does it tell us about changes in the martian surface environment over time?

- What metamorphic and thermal alteration processes have been active on Mars? What secondary mineralogies and lithologies have been produced? How pervasive are they on regional and global scales? Have geothermal and hydrologic processes interacted to produce hotsprings or other hydrothermal activity?

- What is the internal structure of Mars? How siesmically active is the martian crust today? How thick is it? is the crust of the northern plains thinner than that of the Southern Highlands? Is there evidence of isostatic compensation of the crust anywhere? Is there evidence of any global scale horizontal movement of the crust? What is the density and probable composition of the mantle of Mars? Does the martian crust or mantle contain any low velocity layers indicative of plastic behavior or magmatic material? What is the size of the core of Mars, and what is it made of? Is there any active magnetic field present today at a measurable level? Did Mars once have an active magnetosphere? When did it become inactive, and why?

- How does the history of Mars as a planet compare to that of the Moon and the Earth? Do they share a common history of accretion, differentiation and thermal processing? At what stages were these planets alike, and when did they diverge? Are the geological processes that have shaped the surface of ancient Mars still active today, and at what level? How do they compare to the processes that have shaped the face of the Earth through time? Can Mars serve as a model for conditions on the ancient Earth that are no longer accessible to us, given the contained geological activity of our planet?

Ralph P. Harvey
Department of Geology, 112 Smith Building
Case Western Reserve University
Cleveland OH 44106-7216
rph@po.cwru.edu